TOWARD A BETTER UNDERSTANDING OF THE IMPACT OF INFORMATION TECHNOLOGY INTERVENTIONS IN HEALTH CARE

by

Tiago Kuse Colicchio

A dissertation submitted to the faculty of
The University of Utah
in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

Department of Biomedical Informatics

The University of Utah

May 2018

The University of Utah Graduate School

STATEMENT OF DISSERTATION APPROVAL

The dissertation of **Tiago Kuse Colicchio**

has been approved by the following supervisory committee members:

Scott P. Narus	, Chair	**11/22/2017** Date Approved
Guilherme Del Fiol	, Member	**11/22/2017** Date Approved
Julio C. Facelli	, Member	**11/22/2017** Date Approved
Watson A. Bowes III	, Member	**11/22/2017** Date Approved
Debra L. Scammon	, Member	**11/22/2017** Date Approved

and by **Wendy W. Chapman** , Chair/Dean of

the Department/College/School of **Biomedical Informatics**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

Although Electronic Health Record (EHR) systems have recently achieved widespread adoption in the U.S., our understanding of their impact on care outcomes is still limited. Current literature has produced mixed results due to the use of non-standardized measurements and weak research designs. In this dissertation, 4 studies are conducted to develop a systematic methodology for detecting near real-time performance changes during EHR implementations. It also explores factors that can affect outcomes during a commercial EHR implementation.

The first study assesses the current state of the literature on health IT adoption to identify the most commonly reported outcome measures and proposes a taxonomy to classify these measurements.

The second study expands the first study by identifying additional measures through semistructured interviews with experienced clinical and administrative leaders from a large care delivery system. We also collect input from national informatics experts who suggested additional relevant measures.

The third study is a robust longitudinal analysis including several measures from our larger inventory that were used for monitoring a large-scale commercial EHR implementation and detected patterns of impact and mixed time-sensitive effects across geographically dispersed settings from an integrated care delivery system.

The fourth study is a qualitative analysis guided by the quantitative results of the third

study. We identified several factors that may have contributed to performance changes detected by our methodology.

In summary, this dissertation will help the broader medical and informatics communities by informing *what* and *how* to continuously monitor future similar implementations. First, it contributes to the identification of relevant outcomes likely impacted by health IT interventions. Second, it combines these outcome measures with a robust interrupted time-series design, producing a systematic methodology that allows earlier and potentially more precise detection of unexpected effects, and implementation of effective response to mitigate negative impacts. Last, the identification of factors that may impact outcomes during and following an EHR implementation and covariates to measure them will empower researchers in charge of future evaluations, hopefully increasing the understanding of the full impact of health IT interventions.

To Vanessa and Ryan.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to express a special appreciation to my advisor Scott Narus. Under his mentorship I was able to build my research skills on top of my business skills. Scott's influence and extensive knowledge of Intermountain Healthcare's complex processes were of paramount importance to my research.

I also thank the members of my committee, Guilherme Del Fiol, Julio Facelli, Debra Scammon (Debbie), and Watson Bowes (Len) who contributed with their expertise and provided me intellectual advice to complete this research.

Guilherme provided substantial contributions to both the design, data analysis and interpretation, and manuscript preparation of each of the studies in this dissertation. His ideas were crucial for the success of each of these studies. Guilherme acted as a co-mentor during my entire journey in the program – and even before I joined the program. I was extremely fortunate to have him on my supervisory committee.

Julio was directly responsible for the conception the whole idea behind my research. He helped me to visualize the unique opportunity to analyze the impact of a large-scale electronic health record system implementation on several aspects of care. His insightful feedbacks were very important for the completion of this research.

Debbie helped me to make each of the manuscripts and the final dissertation much more insightful. With her strong business background, she always visualized important opportunities for improvement from the perspective of health care leaders.

Len opened several doors at Intermountain and helped me to identify key personnel for an extensive interview process. His clinical background was very important to adapt some of my studies that targeted a more clinical-oriented audience.

I wish to express special gratitude to Greg Stoddard who was extremely important for the development of the methodology used in two of the studies in this dissertation. I would not have been able to finish this work without his help.

I would like to thank all the faculty members of the Department of Biomedical Informatics for sharing their knowledge and experience with me. I am especially grateful to Wendy Chapman, Catherine Staes, and Charlene Weir for their enthusiasm and guidance, and to Damian Borbolla for his contribution to two studies in this dissertation, and, of course, for the many barbecues shared.

I wish to thank all my classmates in the Department of Biomedical Informatics and the administrative staff, especially Tahanie Branz, Barbara Saffel, and JoAnn Thompson, for their help in the past 4 years.

I would like to express especial gratitude to Intermountain Healthcare and the Homer Warner Center for Informatics Research for their financial support for this project.

Most of all, I would like to thank my family, my wife Vanessa for her endless support, love, patience, and encouragement, and my son Ryan and our lovely dog Zulu for making my journey so much fun.

CHAPTER 1

INTRODUCTION

1.1 Objectives and Research Questions

The overall goal of this dissertation is to develop a systematic methodology for detecting near real-time performance changes during electronic health record (EHR) system implementations and to increase our understanding of the full impact of such interventions. Adoption and use of multifunctional EHR systems have significantly increased in the U.S. [1-2], partially due to positive outcomes associated with such tools [3-5], and financial incentives provided by the U.S. federal government [6-7]. As a result of the increased use and adoption of EHRs, the literature on this topic has also increased [8]. However, due to the use of simple, nonstandardized measurements and limitations in research designs and reporting, previous studies have produced mixed results, leaving unanswered questions as to the impact of health IT adoption. The main hypothesis of this dissertation is that our proposed methodology allows detection of a broad range of time-sensitive performance changes introduced by a commercial EHR implementation on quality, productivity and safety outcomes, and that complementary changes, associated or not with the new EHR, may affect these outcomes.

In the 4 studies to be presented, the following aims and research questions were explored:

1. Aim 1: To identify the most commonly reported outcome measures for assessing health IT interventions. Research questions: What are the most commonly reported outcome measures for assessing health IT interventions (Chapter 3)? Do commonly used measures allow development of a taxonomy by which such measures could be classified?
2. Aim 2: To assess whether the most commonly reported measures from the literature provide comprehensive coverage of care processes likely impacted by health IT adoption. Research questions: Do the most commonly reported measures from the literature provide comprehensive coverage of care processes likely impacted by health IT interventions (Chapter 4)? What are the most relevant outcome measures for assessing EHR implementations according to subject-matter experts?
3. Aim 3: To test a methodology for detecting performance changes and patterns of impact on quality, productivity, and safety outcomes during a large-scale EHR implementation. Research question: Can a systematic methodology using outcome measures likely impacted by EHR implementations detect patterns of impact across geographically dispersed settings of a phased EHR implementation (Chapter 5)?
4. Aim 4: To identify factors impacting quality, productivity, and safety outcomes during a large commercial EHR implementation. Research questions: What factors can impact care outcomes during a commercial EHR implementation (Chapter 6)? What covariates with data available in electronic format can be measured for monitoring factors affecting care outcomes during an EHR implementation?

1.2 Rationale for Analysis

Although adoption and use of EHR systems have increased in the U.S., especially since 2011 when the first stage of the Meaningful Use program started to be implemented [1-2], our understanding of how they impact health care organizations and health care outcomes is still limited. While some studies show positive results associated with health IT adoption, such as improving productivity [9] and quality of care [10], and diminishing errors and health care cost [11-12], others show the opposite, even within highly computerized environments [13-15]. In a recent systematic review commissioned by the Office of the National Coordinator for Health IT (ONC), Jones et al. [8] analyzed health IT adoption studies published between 2010 and 2013, and concluded that most studies present positive outcomes; however, they also concluded that current research still reports mixed results, and it has not increased our understanding of the effect of health IT adoption. According to their analysis, further research is necessary to understand why some providers thrive, while others struggle when adopting health IT tools. Possible contributing factors to these gaps include an insufficient amount of information about settings, population, implementation strategy and EHR capabilities tested, and an often small and nonstandard set of measures used in each study.

Similar to large-scale changes observed in other industries [16], an EHR implementation is a complex, ongoing process that introduces sociotechnical changes that iteratively evolve over time [17], exposing end-users to a learning curve of up to 2 years [18]. Previous research suggests that when an intervention has a longitudinal effect – which is the case for EHR implementations – interrupted time-series design is the most suitable design to avoid biases caused by time-sensitive variations not detected by simple pre-post statistical comparisons [19]. Despite the recommendations, health IT adoption studies are primarily pretest-posttest comparisons without a clear relationship between the time when data were collected after implementation and the particular phase of the implementation at that point in time. This may contribute to the mixed results commonly reported in the literature.

Studies evaluating the impact of IT adoption in other industries such as retail, finance, and transportation demonstrate that IT adoption rarely produces positive results if not accompanied by complementary changes or investments (e.g. proper planning and training, upgrading IT infrastructure, adapting workflows, etc.) [20]. These studies have identified several complementary changes that account for the major part of improvements observed after IT adoption [21]. However, evaluations of IT adoption in the health care industry have primarily focused on comparisons of outcome changes before and after EHR implementations, without exploring *what* and *how* complementary factors introduced by such implementations contributed to the changes observed [22].

In this dissertation, we test the hypothesis that by combining a wide range of relevant measures of quality, productivity, and safety outcomes likely impacted by health IT interventions, tracked on an appropriate frequency using a robust time-series design, we can detect various performance changes during EHR implementations. We also explore factors affecting these outcomes over time, to hopefully increase our understanding of the full impact of health IT adoption. In Chapter 3, we present a secondary analysis of the studies evaluated by Jones et al.[8] to identify the most commonly reported measures in evaluations of health IT adoption, and develop a taxonomy to classify these measures into various measurement types. We present additional measures that were identified through semistructured interviews with experienced health care leaders and online surveys with informaticists (Chapter 4), and were tested in several inpatient and outpatient settings from a large care delivery system implementing a commercial EHR (Chapter 5). Finally, we explore factors contributing to performance changes on the outcomes to further clarify the impact of EHR implementations on health care outcomes and elicit potential covariates for monitoring these factors in future similar evaluations (Chapter 6).

This project was coordinated with guidance from an experienced panel of informatics and business experts at the University of Utah and Intermountain Healthcare. The Institutional Review Board (IRB) of Intermountain Healthcare approved the study under protocol 1040351.

1.3 References

[1] Adoption of electronic health record systems among U.S. non-federal acute care hospitals: 2008-2015 [Internet]. [cited 2017 May 10]. Available from: https://dashboard.healthit.gov/evaluations/data-briefs/non-federal-acute-care-hospital-ehr-adoption-2008-2015.php

[2] Office-based physician electronic health record adoption [Internet]. [cited 2017 May 10]. Available from: / https://dashboard.healthit.gov/quickstats/pages/physician-ehr-adoption-trends.php

[3] Ciemins EL, Coon PJ, Fowles JB, Min S. Beyond health information technology: critical factors necessary for effective diabetes disease management. J Diabetes Sci Technol. 2009 May;3(3):452–60.

[4] Pöder U, Fogelberg-Dahm M, Wadensten B. Implementation of a multi-professional standardized care plan in electronic health records for the care of stroke patients. Journal of Nursing Management. 2011 Sep 1;19(6):810–9.

[5] Adler-Milstein J, Salzberg C, Franz C, Orav EJ, Newhouse JP, Bates DW. Effect of electronic health records on health care costs: longitudinal comparative evidence from community practices. Ann Intern Med. 2013 Jul 16;159(2):97–104.

[6] The White House archives. [Internet]. [cited 2017 May 10]. Available from:

http://georgewbush-whitehouse.archives.gov/news/releases/2004/04/20040427-4.html

[7] HITECH Act § 13400(5).

[8] Jones SS, Rudin RS, Perry T, Shekelle PG. Health information technology: an updated systematic review with a focus on meaningful use. Ann Intern Med. 2014 Jan 7;160(1):48–54.

[9] Garrido T, Jamieson L, Zhou Y, Wiesenthal A, Liang L. Effect of electronic health records in ambulatory care: retrospective, serial, cross sectional study. BMJ. 2005 Mar 12;330(7491):581.

[10] Wang JJ, Sebek KM, McCullough CM, Amirfar SJ, Parsons AS, Singer J, et al. Sustained improvement in clinical preventive service delivery among independent primary care practices after implementing electronic health record systems. Prev Chronic Dis. 2013;10:E130.

[11] Abramson EL, Barron Y, Quaresimo J, Kaushal R. Electronic prescribing within an electronic health record reduces ambulatory prescribing errors. Jt Comm J Qual Patient Saf. 2011;37(10):470-8.

[12] Zlabek JA, Wickus JW, Mathiason MA. Early cost and safety benefits of an inpatient electronic health record. J Am Med Inform Assoc. 2011;18(2):169-72.

[13] Singh H, Thomas EJ, Sittig DF, Wilson L, Espadas D, Khan MM, et al. Notification of abnormal lab test results in an electronic medical record: do any safety concerns remain? Am J Med. 2010 Mar;123(3):238–44.

[14] Penfold R, Zhang F, Soumerai S. Impact of electronic health record transition on behavioral health screening. Psychiatr Serv. 2012 Mar;63(3):256–61.

[15] Fleming NS, Becker ER, Culler SD, Cheng D, McCorkle R, Graca B da, et al. The Impact of electronic health records on workflow and financial measures in primary care practices. Health Serv Res. 2014;49(1pt2):405–420.

[16] Moore AP, Ellison RJ, Linger RC. Ultra large scale systems [Internet]. [cited 2017 May 10]. Available from: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA388771 on 3 February, 2017.

[17] Sittig DF, Singh H. A new sociotechnical model for studying health information technology in complex adaptive healthcare systems. Qual Saf Health Care. 2010 Oct 1;19(Suppl 3):i68–74.

[18] Abramson EL, Malhotra S, Osorio SN, Edwards A, Cheriff A, Cole C, et al. A

long-term follow-up evaluation of electronic health record prescribing safety. J Am Med Inform Assoc. 2013 Jun;20(e1):e52–58.

[19] Nelson BK. Time series analysis using autoregressive integrated moving average (ARIMA) models. Acad Emerg Med. 1998 Jul 1;5(7):739–44.

[20] Brynjolfsson E, Hitt LM. Beyond the productivity paradox. Commun ACM. 1998;41(8):49–55.

[21] Brynjolfsson E, Hitt LM. Computing productivity: firm-level evidence. Rev Econ Stat. 2003 Nov 1;85(4):793–808.

[22] Kellermann AL, Jones SS. What it will take to achieve the as-yet-unfulfilled promises of health information technology. Health Aff. 2013 Jan 1;32(1):63–8.

CHAPTER 2

BACKGROUND

2.1 Health Information Technology Adoption in the U.S.

An Electronic Health Record (EHR) system is defined by the Department of Human and Health Services (DHHS) as "*An electronic record of health-related information on an individual that: (A) includes patient demographic and clinical health information, such as medical history and problem lists; and (B) has the capacity: to provide clinical decision support; to support physician order entry; to capture and query information relevant to health care quality; and to exchange electronic health information with, and integrate such information from other sources*" [1]. EHRs have a long history in the U.S. health care system, with the initial developments dated from the early 1970s [2]. Initially, some EHRs focused on hospital billing and scheduling systems while others computerized clinical processes to help improve medical care. The first clinical-oriented EHRs developed in the U.S., between the 1970s and 1980s, include widely known systems developed at distinguished tertiary-care hospitals such as the Health Evaluation through Logical Processing (HELP) system developed at LDS Hospital [3]; the Computer-stored Ambulatory Record (COSTAR) system developed at Massachusetts General Hospital [4]; the Problem Oriented Medical Record System (PROMIS) system developed at University of Vermont Medical Center [5]; the Regenstrief Medical Record

System (RMRS) developed at Indiana University Medical Center [6]; and The Medical Record (TMR) system developed at Duke University Medical Center [7]. Decentralized computer applications were also developed in multiple Veterans Health Administration sites during the same period [8]. Such applications became the foundation of the widely known Veterans Integrated System Technology Architecture (VISTA) EHR, officially adopted in 1996 [9]. In the early 1990s, evidence of problems related to the paper record led the Institute of Medicine (IOM) to advocate a shift from a paper-based to an electronic medical record [10]; however, widespread adoption of EHR systems in the U.S. would still take several years to come to fruition [2].

In the late 1990s and early 2000s, studies demonstrating advantages associated with EHR adoption, such as improving quality of care and patient safety [11-14], attracted attention from government agencies and policy makers. In 2004, the U.S. federal government issued an executive order to provide financial incentives to increase health IT adoption in the U.S. [15], and in 2009, the Health Information Technology for Economic and Clinical Health (HITECH) act was signed into law establishing the Meaningful Use program [16]. The program contributed to increasing EHR adoption among U.S. care delivery systems to unprecedented rates. In 2009, EHR adoption among office-based physicians was still below 50% [17]; after implementation of Meaningful Use Stage 1, studies of the same population demonstrated that adoption had increased to 72% [18]. An even greater change was observed in U.S. hospitals. In 2010, around 16% of U.S. hospitals had a basic EHR; after implementation of Meaningful Use Stage 1 this number increased to 59% [19]. In 2015, 96% of U.S. hospitals and 78% of office-based physicians had adopted a certified EHR [19-20].

As a result of the increased adoption of EHR systems, the literature exploring their impact on health care outcomes is also rapidly increasing [21]. Several systematic reviews have analyzed studies on the impact of health IT adoption. The studies report on different outcomes, such as quality, productivity and safety; review different health IT tools, including multifunctional EHRs; cover both ambulatory and nonambulatory care settings; and include U.S. and non-U.S. health care organizations [21-24]. Such reviews found that health IT adoption studies more frequently report positive outcomes associated with EHR adoption and use [21-24], and that the Meaningful Use program has contributed to the increased positive outcomes reported [24]. However, several years after the early EHR development efforts, and despite the increased adoption rate in recent years, the same reviews also found several studies that produced mixed or negative results, leaving unanswered questions on the full impact of health IT adoption [21-24].

Buntin et al. [24] conducted a systematic review to evaluate studies focused on the effects of health IT adoption published between 2007 and 2010. They found that health IT adoption was associated with positive outcomes in two-thirds of the cases; however, they also found mixed-positive (e.g., overall positive conclusion with at least one negative finding) or negative results in one-third of studies assessed. In another systematic review commissioned by the Office of the National Coordinator for Health IT (ONC), Jones et al. [21] used the same methods as Buntin et al. to analyze studies published between 2010 and 2013. Similar to the previous review, they concluded that most studies present positive outcomes while a substantial number of studies still present neutral, mixed-positive, or negative results. Examples of the latter in ambulatory settings include the impact of EHR implementation on behavioral health screening, showing that compliance rates dropped from 83% to 55% immediately after implementation and did not return to baseline levels until 3 years postimplementation [25], and significantly lower odds that patients received depression treatment after EHR adoption [26]. Examples of negative results in hospital settings include high rates of prescribing error associated with e-Prescribing [27], adoption of advanced EHR capabilities associated with significant decreases in care quality for acute myocardial infarction and heart failure patients [28], and a significant increase in hospital costs [29]. Jones et al. [21] suggest that, due to the mixed results reported, current research has failed to increase our understanding of the impact of health IT adoption, and that with the increasing adoption of EHRs, it is no longer sufficient to ask whether health IT creates value or not; therefore, future research should focus on understanding *how* to realize value from health IT, as opposed to the traditional approach of exploring *if* health IT adds value to health care outcomes. Moving forward, changing the research approach will require more robust research designs, as we demonstrate in the subsequent sections of this chapter.

2.2 Outcome Measurements for Evaluations of Health IT Adoption

Reproducibility of scientific studies has become a significant challenge in the biomedical domain. Researchers evaluating the likelihood of reproducing biomedical studies estimate that over 75% of biomedical research cannot be reproduced through confirmatory studies, potentially leading to wasted time and money [30-31]. The problem, often referred to as the “reproducibility crisis,” has attracted attention from biomedical journals, funding agencies, and the larger scientific community due to an increasing concern with the possibility of having the majority of scientific findings unable to stand the test of time [32]. Among the reasons for the high irreproducibility rate is the use of poor research designs, including the use of heterogeneous, study-specific, and non-agreed outcomes [33]. In health IT adoption research, the vast majority of studies use simple, nonstandardized measurements [21], and frequently assess a small number of outcomes [34-43], even when evaluating complex sociotechnical changes such as implementation of multifunctional EHR systems [25-26,44-48]. From 107 studies conducted in primary care settings evaluated by Jones et al. [21], 22 (21%) studies evaluated the impact of multifunctional EHR systems adoption [25-26, 38, 44-62], and reported a total of 50 different measures used to assess the intervention; from those, 36 (72%) measures were study specific whereas only 14 (28%) measures were used in 2 or more studies. Such cases provide an example of the frequent use of heterogeneous and study-specific measurements in health IT adoption research, and of the barriers limiting comparison of outcomes across studies. Future systematic reviews like those by Buntin et al. [24] and Jones et al. [21] would benefit from evaluating studies that report more standardized measurements that could facilitate comparison across them, hopefully leading to a better understanding of *how* health IT adoption affects care delivery organizations. However, such measures are not available in the literature and the development of an inventory of unequivocal and universally agreed measurements for assessing health IT interventions is necessary to facilitate reporting and comparison of outcomes across future studies, hopefully facilitating their reproducibility as well.

2.3 Longitudinal Characteristic of EHR Implementations

The health care system is a complex ecosystem that deals with constant adaptation to ever increasing medical knowledge [63], applied in high-pressure, fast-paced, and distributed care delivery settings [64]. In such a complex environment, implementation of a new or updated EHR system will inevitably add to the complexity of the several aspects of care with which it interacts [65]; and such an impact is an ongoing process that may affect the care delivery organization from months to years [25]. In a recent study, Samal et al. [66] evaluated the impact of Meaningful Use Stage 1 on the quality of care provided by physicians at one hospital in Massachusetts. They collected quality measures for 3 months and compared the outcomes of care delivered by Meaningful Use adopters and nonadopters. Their findings did not show a significant difference between the 2 groups. However, Kern et al. [67] criticized their methods and the small period of analysis due to the fact that studies have demonstrated that even 2 years after an EHR implementation clinicians could still be in a learning curve, dealing with iterative refinements common to such implementations [68]. Most studies evaluating the impact of health IT adoption have been conducted during or after the EHR implementation, comparing outcomes before and after the intervention (EHR go live). However, previous research suggests that in studies with a longitudinal effect, interrupted time-series design is the best option to avoid biases caused by variations not considered in simple statistical comparison of means [69]. Mylene Lagarde [70] presents 4 examples of common biases in pretest-posttest studies comparing means before and after intervention. They are:

1. Constant trend: an outcome with a constant upward trend started before intervention that was constant during the whole study period will automatically present a higher

outcome after intervention compared to baseline, but such an increase may not have been caused by the intervention itself.

2. Constant trend before intervention: when an upward trend before intervention is replaced by a flatter or stationary trend after intervention, a simple comparison of means would show a misidentified improvement.
3. Seasonal effects: seasonal effects can distort the means due to high or low peaks not identified by a simple comparison of means.
4. Peak after intervention: when an abrupt high peak right after intervention is observed in an outcome with a trend sloping downward, it suggests a problem about the sustainability of the effect not detected by the comparison of means. In addition, it could suggest an improvement when in fact the intervention only changed the direction of the trend.

Few cases of studies evaluating the impact of health IT adoption with longitudinal data are available in the literature, and when available, they use a small number of measures and poor research designs. One of the rare examples of such longitudinal analysis is an evaluation of the impact of EHR implementation in clinical preventive services in primary care settings in New York City [71]. In this study, researchers evaluated 4 preventive care measures and analyzed the trend of measures during a period of 2 years after implementation, tracking averages for each trimester. They found significant improvements and identified an upward trend for all measures; however, their analysis did not contemplate a baseline period before EHR implementation, which could have led to an incorrect conclusion based on the biases mentioned above.

In the case of a large EHR implementation, interrupted time-series design can be an effective method to understand how the changes introduced by the implementation impact a health care system over time. This type of design is more effective when it includes a large number of data points, and a baseline period, which can aid in understanding the real impact of the intervention, as demonstrated by studies with other types of time-sensitive interventions in various fields such as environmental policies [72], economics [73] and health policies [74]. A study conducted by van Driel et al. [75] to explore the effect of prescribing policies favoring selected H2-antihistamines and proton pump inhibitors (PPI), to decrease overall consumption of acid suppressants and cost, concluded that although prescription of the preferred drugs increased, such policies failed to control cost due to the use of multiple nonrecommended drugs, and, as demonstrated by the authors, such a conclusion could only be reached with a pre-post longitudinal study evaluating the effect of the policies on prescription of multiple drugs over time. The use of control sites in longitudinal studies is also recommended whenever possible, to overcome the confounding effect of other events not detected by assessing isolated intervention sites [70]. Soumerai et al. [76] demonstrated that a Medicaid reimbursement policy that restricted the use of 3 drugs per patient 60 years old or older during a specific period in the state of New Hampshire was associated with an increase in admissions to nursing homes. Wager et al. [77] analyzed their study and concluded that such an association was made possible by the use of claims data from the state of New Jersey as a control cohort, since this state did not implement such a policy. Given the time-sensitive effect of EHR implementations, including their potential for impacting both organizational culture [78] and care outcomes over time [25], the use of a more robust methodology is necessary in order to increase the understanding of the full impact of IT interventions in health care. This methodology should use a longitudinal analysis with control sites and baseline data to more effectively monitor the impact of health IT interventions and to identify (1) unexpected effects introduced both during the transition and after the new system has been stabilized, (2) seasonal effects, and (3) time to recover to baseline performance. In addition to improved design, it should include a comprehensive set of relevant outcome measurements, covering a wide spectrum of care processes likely impacted by health IT interventions.

In Chapter 5, we test the use of a proposed methodology that adheres to the previously mentioned recommendations. We use this method to monitor a large commercial EHR implementation tracking several outcome measures of quality, productivity, and safety care processes extracted from the literature and outcomes suggested by experienced heath care leaders and informatics experts on a monthly basis, with baseline data and control sites. We evaluate the implementation of the Millennium EHR developed by Cerner Corporation, Kansas City, MO, U.S. at Intermountain Healthcare, a not-for-profit integrated care delivery system of 22 hospitals and over 185 ambulatory care clinics covering Utah and southern Idaho. Intermountain Healthcare is replacing a group of long-used and stable homegrown systems with Cerner's EHR. Given the size of the Intermountain care delivery system, the implementation of the new EHR uses a staggered schedule with multiple phases, each phase comprising a group of hospitals and clinics from the same geographical area. While the enterprise implementation will be phased, the introduction of the new EHR in each region will use a "big bang" strategy, replacing all legacy systems at once within that region.

Due to the high cost and complexity involved in EHR implementations, the definition of implementation strategy and timeline of settings to be implemented – especially in large care delivery systems such as Intermountain Healthcare – are naturally business-driven decisions; in such cases, randomization of intervention and control settings is virtually impossible, and confirmatory studies are also difficult to conduct. However, the staggered approach adopted by Intermountain Healthcare allowed for multiple tests of our methodology in different implementation regions that received the implementation at different points in time, producing subsequent confirmatory tests of our methodology, attesting to its efficacy for detecting patterns of impact and various performance changes during a large-scale commercial EHR implementation.

2.4 Complementary Changes Introduced by IT Adoption

During the decades following World War II, advancements in computer technology produced an increasing investment in acquisition of IT infrastructure in both manufacturing and services industries. Although the services sector invested substantially more than manufacturing, such an investment was not reflected in increased productivity [79]. This phenomenon is known as the "productivity paradox," a concept first introduced by the economist Steven Roach in 1987 [80]. The paradox had a higher impact on the services sectors mostly due to their inherent complexity. Services transactions are idiosyncratic and difficult to represent and measure, and are processed through complex workflows. Since the health care industry went digital after other services industries [81], initial assessments of the problem involved industries such as retail, finance, and transportation, and, as a result, an increased understanding of the factors contributing to the productivity paradox were mitigated in these industries first, but consequently still affect the health care industry today [82]. The causes of the productivity paradox observed in other industries are attributable to the need for complementary changes or investments (e.g., proper planning and training, upgrading IT infrastructure, adapting workflows, etc.). Experts estimate that for every dollar of IT invested, there are several dollars of organizational investments that generate the large increases in productivity and value [83]. The same experts conclude that IT adoption alone rarely produces positive results if not accompanied by these complementary factors. However, evaluations of IT adoption in the health care industry have primarily focused on comparisons of outcome changes before and after EHR implementations, without exploring *what* and *how* organizational factors can affect care outcomes [84]. In the present research, we attempt to explore the factors that may have contributed to performance changes on quality, productivity, and safety outcomes detected during a commercial EHR implementation. We also identify potential covariates that can be measured with data available in electronic format for monitoring these factors in near real-time, to improve the capacity of our methodology to detect a cause-and-effect relationship between health IT adoption and performance changes on health care outcomes.

2.5 References

[1] 45 C.F.R. § 170.101B.4.

[2] Evans RS. Electronic health records: then, now, and in the future: IMIA Yearbook [Internet]. 2016 May 20 [cited 2016 May 23];25(Suppl. 1). Available from: http://www.schattauer.de/index.php?id=1214&doi=10.15265/IYS-2016-s006

[3] Pryor TA, Gardner RM, Clayton PD, Warner HR. The HELP system. J Med Syst 1983 Apr;7(2):87-102.

[4] Barnett GO. Computer-stored ambulatory record (COSTAR) U.S. Dept. of

Health, Education, and Welfare, Public Health Service, Health Resources Administration, National Center for Health Services Research in [Rockville, MD.]; 1976. 40 p.

[5] Schultz JR, Cantrill SV, Morgan KG. An initial operational problem oriented medical record system for storage, manipulation and retrieval of medical data. AFIPS Conference Proceedings. 1971;38.

[6] McDonald CJ, Overhage JM, Tierney WM, Dexter PR, Martin DK, Suico JG, et al. The Regenstrief medical record system: a quarter century experience. Int J Med Inform. 1999 Jun;54(3):225–53.

[7] Stead WW, Hammond WE. Computer-based medical records: the centerpiece of TMR. MD Comput 1988 Sep-Oct;5(5):48-62.

[8] M.T. Ivers, G.F. Timson, H. von Blankensee, G. Whitfield, P.D. Keltz, C.N. Pfeil, Large-scale implementation of compatible hospital computer systems within the Veterans Administration, in: proceedings of the sixth annual symposium on computer applications in medical care, 1983, pp. 53–56.

[9] Brown SH, Lincoln MJ, Groen PJ, Kolodner RM. VistA—U.S. Department of Veterans Affairs national-scale HIS. Int J Med Inform. 2003 Mar;69(2–3):135–56.

[10] Institute of Medicine. The computer-based patient record: an essential technology for health care. Revised Edition. Dick RS, Steen EB, Detmer DE, editors. Washington, DC: National Academy Press; 1997.

[11] Bates DW, Leape LL, Cullen DJ, et al. Effect of computerized physician order entry and a team intervention on prevention of serious medication errors. JAMA. 1998 Oct 21;280(15):1311–6.

[12] Koide D, Ohe K, Ross-Degnan D, Kaihara S. Computerized reminders to monitor liver function to improve the use of etretinate. Int J Med Inform. 2000 Jan;57(1):11–9.

[13] Gill JM, Ewen E, Nsereko M. Impact of an electronic medical record on quality of care in a primary care office. Del Med J. 2001 May;73(5):187–94.

[14] Dexter PR, Perkins S, Overhage JM, Maharry K, Kohler RB, McDonald CJ. A computerized reminder system to increase the use of preventive care for hospitalized patients. N Engl J Med. 2001 Sep 27;345(13):965–70.

[15] The White House archives. [Internet]. [cited 2017 May 10]. Available from: http://georgewbush-whitehouse.archives.gov/news/releases/2004/04/20040427-4.html

[16] HITECH Act § 13400(5).

[17] Hsiao CJ, Hing E, Socey TC, et al. Electronic medical record/electronic health record systems of office-based physicians: United States, 2009 and preliminary 2010 state estimates. Health E-Stats.2010National Center for Health Statistics. http://www.cdc.gov/nchs/data/hestat/emr_ehr_09/emr_ehr_09.htm.

[18] Heisey-Grove, D, Danehy, L-N, Consolazio, M, Lynch, K, & Mostashari, F (2014). A national study of challenges to electronic health record adoption and meaningful use. Medical Care, 52(2), 144–148. doi:10.1097/MLR.0000000000000038.

[19] Adoption of electronic health record systems among U.S. non-federal acute care hospitals: 2008-2015 [Internet]. [cited 2017 May 10]. Available from: https://dashboard.healthit.gov/evaluations/data-briefs/non-federal-acute-care-hospital-ehr-adoption-2008-2015.php

[20] Office-based physician electronic health record adoption [Internet]. [cited 2017 May 10]. Available from: / https://dashboard.healthit.gov/quickstats/pages/physician-ehr-adoption-trends.php

[21] Jones SS, Rudin RS, Perry T, Shekelle PG. Health information technology: an updated systematic review with a focus on meaningful use. Ann Intern Med. 2014 Jan 7;160(1):48–54.

[22] Chaudhry B, Wang J, Wu S, Maglione M, Mojica W, Roth E, et al. Systematic review: impact of health information technology on quality, efficiency, and costs of medical care. Ann Intern Med. 2006 May 16;144(10):742–52.

[23] Goldzweig CL, Towfigh A, Maglione M, Shekelle PG. Costs and benefits of health information technology: new trends from the literature. Health Aff. 2009 Mar 1;28(2):w282–93.

[24] Buntin MB, Burke MF, Hoaglin MC, Blumenthal D. The Benefits of health information technology: a review of the recent literature shows predominantly positive results. Health Aff. 2011 Mar 1;30(3):464–71.

[25] Hacker K, Penfold R, Zhang F, Soumerai SB. Impact of electronic health record transition on behavioral health screening in a large pediatric practice. Psychiatr Serv. 2012;63(3):256-61.

[26] Harman JS, Rost KM, Harle CA, Cook RL. Electronic medical record availability and primary care depression treatment. J Gen Intern Med. 2012 Aug;27(8):962–7.

[27] Abdel-Qader DH, Harper L, Cantrill JA, Tully MP. Pharmacists' interventions in prescribing errors at hospital discharge: an observational study in the context of

an electronic prescribing system in a UK teaching hospital. Drug Saf. 2010;33(11):1027-44.

[28] Jones SS, Adams JL, Schneider EC, Ringel JS, McGlynn EA. Electronic health record adoption and quality improvement in US hospitals. Am J Manag Care. 2010;16(12 Suppl HIT):SP64-71.

[29] Furukawa MF, Raghu TS, Shao BB. Electronic medical records, nurse staffing, and nurse-sensitive patient outcomes: evidence from California hospitals, 1998-2007. Health Serv Res. 2010;45(4):941-62.

[30] Chalmers I, Glasziou P. Avoidable waste in the production and reporting of research evidence. Lancet. 2009;374:86–89. doi: 10.1016/ S0140-6736(09)60329-9.

[31] Chalmers I, Bracken MB, Djulbegovic B, Garattini S, Grant J, Gülmezoglu AM, Howells DW, Ioannidis JP, Oliver S. How to increase value and reduce waste when research priorities are set. Lancet. 2014;383:156–165. doi: 10.1016/S0140-6736(13)62229-1.

[32] Begley CG, Ioannidis JPA. Reproducibility in science. Circ Res. 2015 Jan 2;116(1):116–26.

[33] Ioannidis JPA. Why most published research findings are false. PLoS Medicine. 2005;2(8):e124.

[34] Dejesus RS, Angstman KB, Kesman R, Stroebel RJ, Bernard ME, Scheitel SM, et al. Use of a clinical decision support system to increase osteoporosis screening. J Eval Clin Pract. 2010.

[35] Spalding SC, Mayer PH, Ginde AA, Lowenstein SR, Yaron M. Impact of computerized physician order entry on ED patient length of stay. Am J Emerg Med. 2011 Feb;29(2):207–11.

[36] Refuerzo J, Straub H, Murphy R, Salter L, Ramin S, Blackwell S. Computerized physician order entry reduces medication turnaround time of labor induction agents. Am J Perinatol. 2011 Apr;28(4):253–8.

[37] Carman MJ, Phipps J, Raley J, Li S, Thornlow D. Use of a clinical decision support tool to improve guideline adherence for the treatment of Methicillin-Resistant Staphylococcus aureus: skin and soft tissue infections. Adv Emerg Nurs J. 2011;33(3):252–66.

[38] Atlas SJ, Grant RW, Lester WT, Ashburner JM, Chang Y, Barry MJ, et al. A cluster-randomized trial of a primary care informatics-based system for breast cancer screening. J Gen Intern Med. 2011;26(2):154-61.

[39] Eaton J, Reed D, Angstman KB, Thomas K, North F, Stroebel R, et al. Effect of visit length and a clinical decision support tool on abdominal aortic aneurysm screening rates in a primary care practice. J Eval Clin Pract. 2012;18(3):593-8.

[40] Gill JM, Mainous AG, 3rd, Koopman RJ, Player MS, Everett CJ, Chen YX, et al. Impact of EHR-based clinical decision support on adherence to guidelines for patients on NSAIDs: a randomized controlled trial. Ann Fam Med. 2011;9(1):22-30.

[41] Stenner SP, Chen Q, Johnson KB. Impact of generic substitution decision support on electronic prescribing behavior. J Am Med Inform Assoc. 2010;17(6):681-8.

[42] Gonzales R, Anderer T, McCulloch CE, Maselli JH, Bloom FJ, Jr., Graf TR, et al. A cluster randomized trial of decision support strategies for reducing antibiotic use in acute bronchitis. JAMA Intern Med. 2013;173(4):267-73.

[43] Moniz TT, Seger AC, Keohane CA, Seger DL, Bates DW, Rothschild JM. Addition of electronic prescription transmission to computerized prescriber order entry: effect on dispensing errors in community pharmacies. Am J Health Syst Pharm. 2011;68(2):158-63.

[44] Adler-Milstein J, Green CE, Bates DW. A survey analysis suggests that electronic health records will yield revenue gains for some practices and losses for many. Health Aff (Millwood). 2013;32(3):562-70.

[45] McCormick D, Bor DH, Woolhandler S, Himmelstein DU. Giving office-based physicians electronic access to patients' prior imaging and lab results did not deter ordering of tests. Health Aff (Millwood). 2012;31(3):488-96.

[46] Herrin J, da Graca B, Nicewander D, Fullerton C, Aponte P, Stanek G, et al. The effectiveness of implementing an electronic health record on diabetes care and outcomes. Health Serv Res. 2012;47(4):1522-40.

[47] Davis AM, Cannon M, Ables AZ, Bendyk H. Using the electronic medical record to improve asthma severity documentation and treatment among family medicine residents. Fam Med. 2010;42(5):334-7.

[48] Bennett KJ, Steen C. Electronic medical record customization and the impact upon chart completion rates. Fam Med. 2010 May;42(5):338–42.

[49] Adler-Milstein J, Jha AK. Organizational complements to electronic health records in ambulatory physician performance: the role of support staff. J Am Med Inform Assoc. 2012;19(4):537-40.

[50] Adler-Milstein J, Salzberg C, Franz C, Orav EJ, Newhouse JP, Bates DW. Effect of electronic health records on health care costs: longitudinal comparative

evidence from community practices. Ann Intern Med. 2013;159(2):97-104.

[51] Cebul RD, Love TE, Jain AK, Hebert CJ. Electronic health records and quality of diabetes care. N Engl J Med. 2011;365(9):825-33.

[52] Damberg CL, Shortell SM, Raube K, Gillies RR, Rittenhouse D, McCurdy RK, et al. Relationship between quality improvement processes and clinical performance. Am J Manag Care. 2010;16(8):601-6.

[53] Feblowitz J, Henkin S, Pang J, Ramelson H, Schneider L, Maloney FL, et al. Provider use of and attitudes towards an active clinical alert: a case study in decision support. Appl Clin Inform. 2013;4(1):144-52

[54] Frimpong JA, Jackson BE, Stewart LM, Singh KP, Rivers PA, Bae S. Health information technology capacity at federally qualified health centers: a mechanism for improving quality of care. Health Serv Res. 2013;13:35.

[55] Furukawa MF. Electronic medical records and efficiency and productivity during office visits. Am J Manag Care. 2011;17(4):296-303

[56] Keehbauch J, Miguel GS, Drapiza L, Pepe J, Bogue R, Smith-Dixon A. Increased documentation and management of pediatric obesity following implementation of an EMR upgrade and education. Clin Pediatr (Phila). 2012;51(1):31-8.

[57] Kern LM, Barron Y, Dhopeshwarkar RV, Edwards A, Kaushal R. Electronic health records and ambulatory quality of care. J Gen Intern Med. 2013;28(4):496-503.

[58] McCullough JS, Christianson J, Leerapan B. Do electronic medical records improve diabetes quality in physician practices? Am J Manag Care. 2013;19(2):144-9.

[59] Poon EG, Wright A, Simon SR, Jenter CA, Kaushal R, Volk LA, et al. Relationship between use of electronic health record features and health care quality: results of a statewide survey. Med Care. 2010;48(3):203-9.

[60] Rappaport DI, Collins B, Koster A, Mercado A, Greenspan J, Lawless S, et al. Implementing medication reconciliation in outpatient pediatrics. Pediatrics. 2011;128(6):e1600-7.

[61] Ryan AM, Bishop TF, Shih S, Casalino LP. Small physician practices in New York needed sustained help to realize gains in quality from use of electronic health records. Health Aff (Millwood). 2013 Jan;32(1):53–62.

[62] Tundia NL, Kelton CM, Cavanaugh TM, Guo JJ, Hanseman DJ, Heaton PC. The effect of electronic medical record system sophistication on preventive healthcare

for women. J Am Med Inform Assoc. 2012. doi: 10.1136/amiajnl-2012-001099.

[63] Densen P. Challenges and opportunities facing medical education. Trans Am Clin Climatol Assoc. 2011;122:48–58.

[64] Sittig DF, Singh H. A new sociotechnical model for studying health information technology in complex adaptive healthcare systems. Qual Saf Health Care. 2010 Oct 1;19(Suppl 3):i68–74.

[65] Wiedemann LA. A look at unintended consequences of EHRs. Health Manag Technol. 2012 Feb;33(2):24–5.

[66] Samal L, Wright A, Healey MJ, Linder JA, Bates DW. Meaningful use and quality of care. JAMA Intern Med. 2014 Jun 1;174(6):997–8.

[67] Kern LM, Kaushal R. Measuring the impact of "meaningful use" on quality of care. JAMA Intern Med. 2014 Jun 1;174(6):998–9.

[68] Abramson EL, Malhotra S, Osorio SN, Edwards A, Cheriff A, Cole C, et al. A long-term follow-up evaluation of electronic health record prescribing safety. J Am Med Inform Assoc. 2013 Jun;20(e1):e52–58.

[69] Nelson BK. Time series analysis using autoregressive integrated moving average (ARIMA) models. Acad Emerg Med. 1998 Jul 1;5(7):739–44.

[70] Lagarde M. How to do (or not to do) … Assessing the impact of a policy change with routine longitudinal data. Health Policy Plan. 2012 Jan 1;27(1):76–83.

[71] Wang JJ, Sebek KM, McCullough CM, Amirfar SJ, Parsons AS, Singer J, et al. Sustained improvement in clinical preventive service delivery among independent primary care practices after implementing electronic health record systems. Prev Chronic Dis. 2013;10:E130.

[72] Box GE, Tiao GC. Intervention analysis with application to economic and environmental problems. J Am Stat Assoc. 1975; 70: 70–9.

[73] Ho AKF, Wan ATK. Testing for covariance stationarity of stock returns in the presence of structural breaks: an intervention analysis. Appl Econ Lett. 2002; 9: 441–7.

[74] Chan SSC, Wong DCN, Fong DYT et al. Short-term impact of new smoke-free legislation on the utilization of a quitline in Hong Kong. Nicotine Tob Res. 2009; 11: 356–61.

[75] Van Driel ML, Vander Stichele R, Elseviers M et al. Effects of an evidence report and policies lifting reimbursement restrictions for acid suppressants: analysis of

the Belgian national database. Pharmacoepidemiol Drug Saf. 2008; 17: 1113–22.

[76] Soumerai SB, Ross-Degnan D, Avorn J, McLaughlin TJ, Choodnovskiy I. Effects of Medicaid drug-payment limits on admission to hospitals and nursing homes. N Engl J Med. 1991 Oct 10;325(15):1072–7.

[77] Wagner AK, Soumerai SB, Zhang F, Ross-Degnan D. Segmented regression analysis of interrupted time series studies in medication use research. J Clin Pharm Ther. 2002 Aug 1;27(4):299–309.

[78] Nowinski CJ, Becker SM, Reynolds KS, Beaumont JL, Caprini CA, Hahn EA, et al. The impact of converting to an electronic health record on organizational culture and quality improvement. Int J Med Inform. 2007 Jun;76, Supplement 1:S174–S183.

[79] Brynjolfsson E. The productivity paradox of information technology. Commun ACM. 1993 Dec;36(12):66–77.

[80] Roach S. Steven. America's technology dilemma: a profile of the information economy. New York : Morgan Stanley, 1987.

[81] Friedman C, Rubin J, Brown J, Buntin M, Corn M, Etheredge L, et al. Toward a science of learning systems: a research agenda for the high-functioning learning health system. J Am Med Inform Assoc. 2015 Jan 1;22(1):43–50.

[82] Wachter, Robert M. The digital doctor: hope, hype, and harm at the dawn of medicine's computer age. McGraw-Hill Education, 2015.

[83] Brynjolfsson E, Hitt LM. Beyond the productivity paradox. Commun ACM. 1998;41(8):49–55.

[84] Kellermann AL, Jones SS. What it will take to achieve the as-yet-unfulfilled promises of health information technology. Health Aff. 2013 Jan 1;32(1):63–8.

CHAPTER 3

HEALTH INFORMATION TECHNOLOGY ADOPTION: UNDERSTANDING RESEARCH PROTOCOLS AND OUTCOME MEASUREMENTS FOR IT INTERVENTIONS IN HEALTH CARE

Tiago K. Colicchio, Julio C. Facelli, Guilherme Del Fiol, Debra L. Scammon, Watson A. Bowes III, Scott P. Narus

Journal of Biomedical Informatics, Volume 73, September 2017, Pages 62-75

https://doi-org.ezproxy.lib.utah.edu/10.1016/j.jbi.2016.07.018

Journal of Biomedical Informatics 63 (2016) 33–44

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Special Communication

Health information technology adoption: Understanding research protocols and outcome measurements for IT interventions in health care

Tiago K. Colicchio [a,*], Julio C. Facelli [a], Guilherme Del Fiol [a], Debra L. Scammon [b], Watson A. Bowes III [a,c], Scott P. Narus [a,c]

[a] Department of Biomedical Informatics, University of Utah, Salt Lake City, UT, USA
[b] Department of Marketing, David Eccles School of Business, University of Utah, Salt Lake City, UT, USA
[c] Medical Informatics, Intermountain Healthcare, Salt Lake City, UT, USA

ARTICLE INFO

Article history:
Received 8 April 2016
Revised 3 June 2016
Accepted 19 July 2016
Available online 20 July 2016

Keywords:
Electronic health records
Medical informatics applications
Adoption
Review

ABSTRACT

Objective: To classify and characterize the variables commonly used to measure the impact of Information Technology (IT) adoption in health care, as well as settings and IT interventions tested, and to guide future research.

Materials and methods: We conducted a descriptive study screening a sample of 236 studies from a previous systematic review to identify outcome measures used and the availability of data to calculate these measures. We also developed a taxonomy of commonly used measures and explored setting characteristics and IT interventions.

Results: Clinical decision support is the most common intervention tested, primarily in non-hospital-based clinics and large academic hospitals. We identified 15 taxa representing the 79 most commonly used measures. Quality of care was the most common category of these measurements with 62 instances, followed by productivity (11 instances) and patient safety (6 instances). Measures used varied according to type of setting, IT intervention and targeted population.

Discussion: This study provides an inventory and a taxonomy of commonly used measures that will help researchers select measures in future studies as well as identify gaps in their measurement approaches. The classification of the other protocol components such as settings and interventions will also help researchers identify underexplored areas of research on the impact of IT interventions in health care.

Conclusion: A more robust and standardized measurement system and more detailed descriptions of interventions and settings are necessary to enable comparison between studies and a better understanding of the impact of IT adoption in health care settings.

1. Background and significance

Health Information Technology (health IT) tools such as Electronic Health Record (EHR) systems have the potential to improve health care outcomes and decrease health care cost [1–3]. Based on previous studies showing such improvements, the U.S. federal government issued an executive order in 2004 to provide financial incentives to increase health IT adoption in the U.S., and five years later the HITECH act was signed into law establishing the Meaningful Use criteria [4,5] as a financial incentive to increase health IT adoption. Such efforts have contributed significantly to increasing EHR adoption in both outpatient and inpatient settings [6]. A basic EHR had been adopted by 48% of office-based physicians in 2013, and by 76% of US hospitals in 2014 [7,8].

Several researchers have assessed the impact of health IT adoption in individual health care settings, and a large number of studies in this area can be found in four systematic reviews covering the period 1995–2013 [9–12]. Research in this area includes studies of interventions in U.S. and non-U.S. ambulatory and non-ambulatory settings with a wide range of characteristics [13–17]. The measurements used to evaluate the effect of the interventions cover many different dimensions of care such as quality of care, efficiency, satisfaction and patient safety.

Although EHR systems comprise a large set of modules and functionality, health IT adoption studies have focused primarily on specific components such as clinical decision support (CDS)

* Corresponding author at: 421 Wakara Way, Suite 140, Salt Lake City, UT 84108-3514, USA.
E-mail address: tiago.colicchio@utah.edu (T.K. Colicchio).

and computerized provider order entry (CPOE) [11,12]. Furthermore, research in this area has shown mixed results of the effectiveness of IT interventions. While some studies show positive results in health care outcomes [18], others show the opposite, even within highly computerized environments [19,20]. In a recent systematic review commissioned by the Office of the National Coordinator for Health IT (ONC), Jones et al. [12] analyzed studies published between 2010 and 2013 and concluded that in addition to mixed results, the current literature has not increased our understanding of the effect of health IT adoption or how it can contribute to improving health care outcomes. Possible contributing factors to these findings include insufficient measurement and reporting of information regarding the implementation and context of health IT use, such as settings, implementation approach, and IT intervention details, as well as the use of non-standardized protocols and simple measurement approaches. Jones and colleagues analyzed and classified the results from the studies according to outcomes (positive or negative), health IT infrastructure (commercial vs. homegrown), and meaningful use functionality used. They did not analyze or categorize the individual outcome measures used to evaluate the effect of IT interventions in health care, nor did they report the characteristics of settings and IT interventions tested. Using the same studies reviewed by Jones et al. [12], here we analyze and categorize the different variables used to evaluate the effectiveness of IT interventions in health care settings. We then use these results to identify potential ways to create a common set of measurements that can be used to evaluate both individual interventions as well as to compare interventions across different settings. We further explore the context of past studies identifying IT interventions tested and the characteristics of settings in which they were examined.

2. Materials and methods

We conducted a descriptive study of the articles included in the review by Jones et al. [12]. We further analyzed these studies according to the following steps: (1) identify the outcome measures used; (2) create a hierarchy and a taxonomy of commonly used measures; (3) compare the measures used in research studies to those commonly required by policy makers and government; and (4) identify characteristics of settings and IT interventions tested. The procedures for these steps are described in the subsequent sections.

2.1. Previous systematic review by Jones et al. [12]

Studies evaluating the impact of IT interventions in health care settings are more commonly available with the increased adoption of EHR systems; as a result, the ONC requested an updated systematic review of such literature. The systematic review was conducted by Jones et al. [12], and the articles included in their final sample are used in the present study for secondary analysis. The search strategy employed by Jones et al. was originally developed by Chaudhry et al. [9], and updated by Goldzweig et al. [10] and Buntin et al. [11]. It includes peer-reviewed, English-language publications evaluating the impact of health IT interventions with functionality encompassed by the meaningful use program. Their final sample includes 236 "hypothesis-testing" and "descriptive quantitative" studies indexed in PubMed covering the period of January 2010 to August 2013. A 5-person technical expert panel guided the systematic review process that included abstracted information about study design; research sites; health IT type appraisal of the studies was performed by dual-review and conflicts were resolved through consensus [12].

2.2. Settings inclusion and exclusion criteria

We excluded studies assessing exclusively specialty care clinics, nursing homes and children's hospitals because these settings are more likely to have patient populations with specific characteristics, and may use specific outcome measures that are not easily generalizable to other settings. Using these exclusion criteria, we first screened the title and abstract of all 236 articles included in Jones et al. [12] original systematic review and excluded 17 studies; in a second screening assessing the methods and results sections we excluded another 11 studies. Fig. 1 presents the procedure for inclusion and exclusion criteria.

2.3. Step 1 - Identification of individual outcome measures

From the 208 studies that fit the inclusion criteria, we identified each individual outcome measure used and mentioned in the methods and/or results sections of the publication. We looked for any measure used as a dependent variable and identified the targeted population. This analysis produced 429 unique measures.

2.4. Step 2 - Development of a taxonomy of commonly used measures

To create a taxonomy of commonly used measures, one of the authors (TKC) first conducted a bottom-up analysis, grouping the measures by similarity into a hierarchy. Similarity was defined by comparing the dependent variables and their targeted populations to identify the variables that measure similar outcomes. In some cases, the terms reported as dependent variables were searched in UpToDate [21] to determine if they are synonyms or if they measure a similar outcome. For example, we searched definitions for the terms "Eye exam", "Retinal exam" and "Retinopathy test" combined with "diabetes mellitus", to determine if they could be labeled as "Diabetic Retinopathy Screening", which was the final term chosen to be used in our hierarchy. We additionally searched some terms in the Systematized Nomenclature of Medicine - Clinical Terms (SNOMED-CT) browser available at the Unified Medical Language System (UMLS) [22], to determine if they are synonyms or share the same parent in the SNOMED-CT hierarchy. Some variables measuring volume of medical orders or health care utilization, such as "laboratory orders" and "readmission rate", were not found in the resources we used and were grouped according to the expert opinion of the authors. Similar to the process used by Wright et al. for creating a taxonomy of CDS tools [23], we conducted a modified Delphi process where the first version of the hierarchy was shared with the study co-authors, who then provided suggestions iteratively until consensus was reached. We also used the Delphi process to reach consensus about the most appropriate nomenclature for each measure, combining the terms used in the included studies, found in online resources, and obtained from the study co-authors. Measures that could not be grouped into a less specific category because they were too specific or unique (used in only one study) were excluded from the hierarchy. After identifying the least specific measures in the highest level of the hierarchy, we grouped them by similarity to identify the taxa that represent these measures. Fig. 2 presents the procedure to identify measures and create the taxonomy, and Fig. 3 provides an example of the bottom-up analysis used to create the hierarchy. Jones et al. [12] classified the studies included in their analysis into three commonly used dimensions of care: quality of care, patient safety and efficiency, according to the aspects of care assessed. In

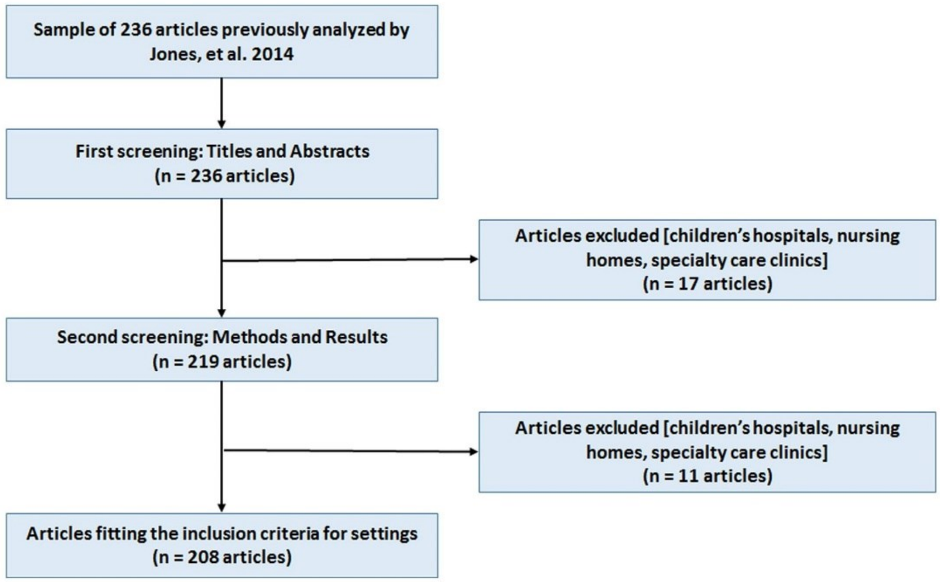

Fig. 1. Flow chart describing the procedures used here for identifying studies that fit the inclusion criteria.

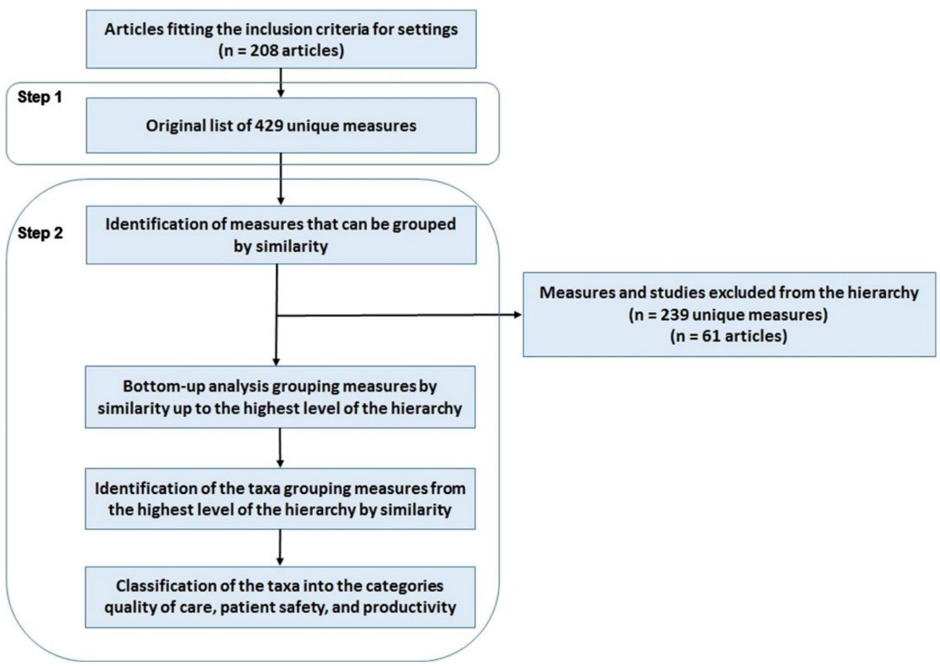

Fig. 2. Procedure to identify measures and create the taxonomy of commonly used measures.

classification of dimensions of care assigned to them by Jones et al. [12], and then grouped the taxa that represent these measures into the same dimensions of care. The dimensions of care represent the three categories of our taxa: quality of care, patient safety, and productivity.

2.5. Step 3 - Comparison of outcome measures against reporting systems

For all measures in the highest level of the hierarchy classified as quality of care or patient safety, we conducted an additional

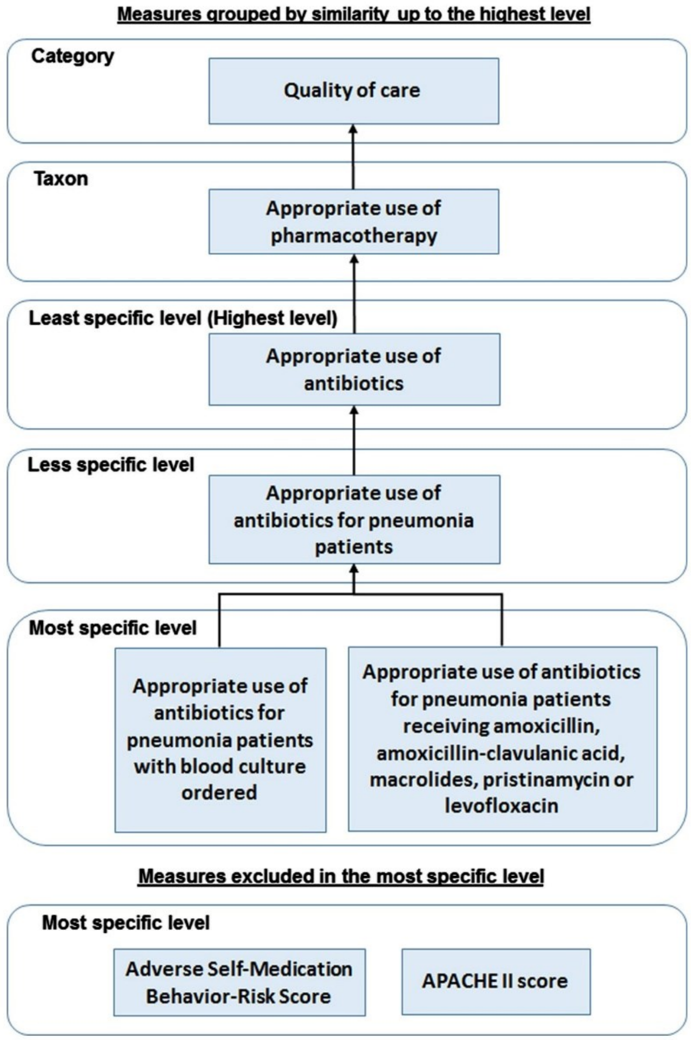

Fig. 3. Example of measures included and excluded from the hierarchy through the bottom-up analysis.

analysis comparing these measures against performance measures commonly required by policy makers and government. In order to determine how readily available the data are to researchers, we identify whether data necessary to calculate these measures are provided by performance measures required by common reporting systems. For ambulatory settings, we used the 2015 version of the Healthcare Effectiveness Data and Information Set (HEDIS) [24]; for non-ambulatory settings, we used the Centers for Medicare and Medicaid (CMS) Hospital Compare measures retrieved from the Hospital Compare data archive dated January 22, 2015 [25]. We chose HEDIS for ambulatory settings because it is commonly required by health insurance companies for billing purposes and is used extensively in biomedical research [26]. We chose CMS Hospital Compare for non-ambulatory because it is used by the government to compare Medicare-certified hospitals in the U.S., and it is also used by consulting entities such as the Joint Commission and the Leapfrog Group [27,28].

2.6. Step 4 - Identification of context domains and IT interventions investigated

To assess the context domains and IT interventions, we reanalyzed the methods and results sections of the remaining 147 articles that represent the measures from the highest level of the hierarchy. For studies in ambulatory settings we identified Clinical Setting (Hospital-based or Non-hospital-based); Practice Type (Primary Care or Mixed – studies were classified as "Mixed" if they included primary and specialty care clinics, meaning that measures used were not specifically applied to specialty care); Organizational Ownership (For profit, Not-for-profit or Public); and Region (Northeast, South, Midwest, West, National or Outside the US. Studies were considered National if researchers used data from national surveys, or settings from two or more regions). For non-ambulatory settings we identified Size (Small (<100 beds), Medium (100–399 beds) and Large ($\geqslant$400 beds)); Teaching Status (Academic hospital or Non-academic hospital); Organizational Ownership (For profit, Not-for-profit or Public); and Region (Northeast, South, Midwest, West, National or Outside the US). We identified the type of IT intervention tested according to the Department of Health and Human Services (DHHS) definition of the components of an EHR [29]. These criteria include EHR; CPOE; CDS; CPOE with CDS; Health Information Exchange (HIE); and Personal Health Records (PHR). For studies testing interventions classified as CDS or CPOE with CDS, we conducted an additional analysis identifying the type of CDS tools tested using the taxonomy of CDS systems developed by Wright et al. [23]. We also compared the outcome measures used with the most common interventions tested.

According to Jones et al. [12], studies frequently provide information on size, location and teaching status of the targeted settings, but few report on other context domains that may impact the adoption experience. We used several methods to address this gap. Some studies clearly stated all information for our analysis in their methods and/or results. In cases where the information was not directly stated, but the name of the study setting was available, we looked for additional information about the facility on the internet, primarily from its official website, or using search methods available online at the American Hospital Directory website [30]. When information was not found using these sources, we contacted the corresponding author for further clarification. If still unsuccessful, we classified the information as "Not Specified".

3. Results

From 147 studies, we identified 15 taxa that represent 79 outcome measures derived from the highest level of our hierarchy. (Note: the number of measures reported here exceeds the number of measures in highest level of our hierarchy because measures used in ambulatory and non-ambulatory settings were counted separately.) Fig. 4 shows the taxonomy of commonly used outcome measures. The complete hierarchy can be accessed in the supplemental material available online. The full list of studies included in this analysis can be found in the reference list of the online supplement. We identified 12 taxa for quality of care, two for productivity, and only one for patient safety. Outcome measures under quality of care ($n = 62$) were by far the most common type of measurement used, more than three times as many measures as those under productivity ($n = 11$) and patient safety ($n = 6$) combined. Ambulatory settings used more measures ($n = 48$) than non-ambulatory settings ($n = 31$). The number of studies assessing each type of setting was similar, with non-ambulatory settings having 79 studies and ambulatory settings having 75.

3.1. Settings characteristics and health IT interventions

Studies included in the Jones et al. [12] systematic review were conducted in a wide range of care settings, covering several U.S. regions and settings outside the U.S., and tested a wide range of health IT interventions.

We identified 16 types of CDS tools used from the 53 types proposed by Wright et al. [23], and one type not included in Wright's article. Table 1 summarizes setting characteristics and interventions and Fig. 5 illustrates the differences between ambulatory and non-ambulatory studies.

3.2. Quality of care measures

Quality of care measures were the most common in both types of setting, as well as the most common category in the taxonomy, with twelve taxa. They were assessed in 98 studies (Tables 1 and 2 of the Supplement). For ambulatory settings, a total of 41 measures were included in our final list. The taxa with the most measures were "test or procedure ordered as preventive care" ($n = 13$ [32%]), followed by "optimal care documented in the patient EHR" ($n = 10$ [24%]) and "appropriate use of pharmacotherapy" ($n = 8$ [20%]). "Blood pressure control" was the most used measure, followed by "breast cancer screening" and "hemoglobin A1c control". Guidelines for diabetes care appear to vary among primary care providers, as the diabetes bundles used differ by at least one component in all of the studies. Table 2 summarizes quality measures in ambulatory settings.

For non-ambulatory settings, 21 measures were included in our final list. The taxa with the most measures were "hospital complication" ($n = 6$ [29%]) and "optimal care documented in patient EHR" ($n = 4$ [19%]). "Hospital length of stay" was the most used measure, followed by "mortality rate" and "appropriate use of antibiotics". Table 3 summarizes quality measures in non-ambulatory settings.

The focus of researchers exploring quality of care varied according to the type of setting evaluated, with ambulatory settings primarily focused on preventive care, and non-ambulatory settings focused on hospital complications.

3.3. Patient safety measures

Patient safety measures were classified into one taxon and used in 31 studies (Tables 3 and 4 of the Supplement). All measures were classified into the taxon "medication safety". In ambulatory settings, only two measures were included in our final list: "medication errors" and "adverse drug events". Safety measures were used in 24 studies conducted in non-ambulatory settings. Four measures were used by researchers working in these settings. "Medication errors" was by far the most common measure used, followed by "medication orders changed" and "adverse drug events". Table 4 summarizes safety measures.

3.4. Productivity measures

Productivity measures were classified into two taxa and used in 25 studies (Tables 5 and 6 of the Supplement). The two taxa identified were "volume of medical orders" ($n = 6$ [55%]) and "health care utilization" ($n = 5$ [45%]). In ambulatory settings, researchers frequently assessed the volume of medical orders for medications, laboratory tests, and imaging tests. For non-ambulatory settings, researchers focused more on emergency departments, with "Emergency Department (ED) length of stay" and "ED visits" being the most used measures. Table 4 summarizes measures of productivity.

3.5. Comparison of measures by IT interventions tested

For ambulatory settings, studies assessing CDS systems more commonly measured "blood pressure control", "osteoporosis screening" and "appropriate use of ACE inhibitor or ARB" when testing "care reminder tools"; "inappropriate use of antibiotics", "medication orders" and "appropriate use of antibiotics" when testing "antibiotic ordering support tools"; and "blood pressure control", "dietary counseling" and "laboratory orders" when testing "condition-specific order set tools". When CPOE with CDS was tested, "medication errors" was the most used measure with both "drug-allergy", "drug-drug" and "drug-condition interaction tools". When EHR was tested, the most used measures were "diabetes bundle", "breast cancer screening" and "chlamydia screening".

For non-ambulatory settings, studies assessing CDS systems more commonly measured "venous thromboembolism rate", "venous thromboembolism prophylaxis" and "in-hospital bleeding

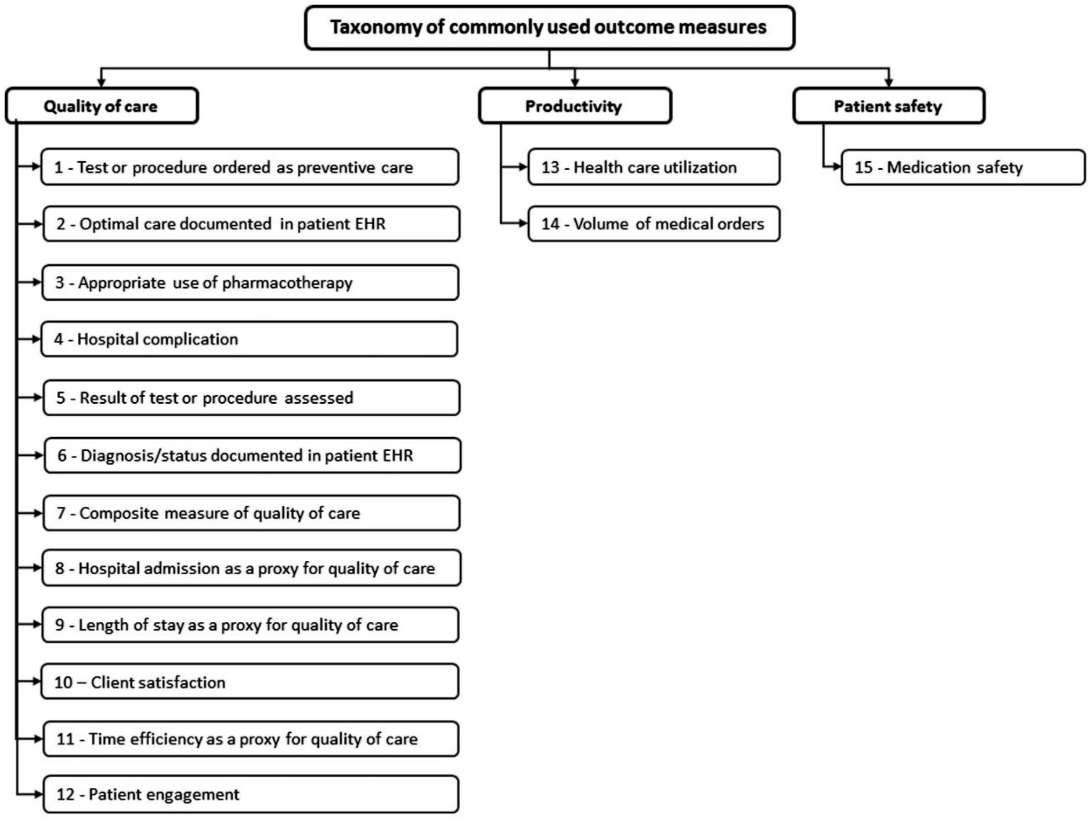

Fig. 4. Taxonomy of commonly used outcome measures.

rate" when testing both "condition-specific order set tools" and "risk assessment tools". "Medication errors" and "blood glucose control" were more commonly used when researchers were testing "medication dose adjustment tools". When CPOE with CDS was tested, researchers more commonly measured "adverse drug events" and "non-recommended medication orders" with both "medication dose adjustment", "drug-drug" and "drug-condition interaction tools". When EHR was tested, "hospital length of stay", "mortality rate" and "ED length of stay" were the most used measures.

3.6. Comparison of measures against reporting systems

Data required for twenty-four measures of quality of care in ambulatory settings can be relatively easily found in the data needed to calculate the measures included in HEDIS. Table 2 presents HEDIS equivalent measures for each item. Comprehensive diabetes care alone provides data for five commonly used measurements: "diabetes bundle"; "hemoglobin A1c screening"; "hemoglobin A1c control"; "nephropathy screening"; and "diabetic retinopathy screening". Non-ambulatory settings have slightly less similarity for measures of quality than ambulatory, but data required for eight measurements can still be found in the data required for the Hospital Compare measures. Table 3 presents Hospital Compare equivalent measures for each item. None of the reporting systems provides data for patient safety measures.

4. Discussion

While many studies assessing the impact of health IT adoption are currently available, there is no study providing an analysis of the literature focused on the research protocols commonly used, nor is there a comprehensive list of outcome measures used in these studies to guide future research. We attempt to fill this gap with information that can be useful in several ways. We enumerate clinical and administrative processes commonly covered by current research. We also provide the first inventory of measures for the impact of health IT based on outcome measures commonly used in previous studies, and linking them to widely used national reporting systems. This inventory has been used to develop a taxonomy for these measures. Such information could help researchers identify candidate measures as well as facilitate comparison of health IT outcomes in future studies. In addition, information about IT interventions tested and settings in which they were examined may help to identify underexplored areas in the research landscape.

From our analysis of IT interventions, we found that clinical decision support is the most common intervention tested. Most studies assessed adherence to evidence-based guidelines presented to clinicians as alerts and reminders. Previous studies have demonstrated that other functions of EHRs are less frequently tested [11,12]. Our study indicates that this finding applies to both ambulatory and non-ambulatory settings. CDS interventions are frequently described in more detail than general EHR

Table 1
Characteristics of setting and IT interventions investigated.

	All studies	Quality of care	%	Productivity	%	Patient safety	%
Ambulatory settings							
Practice type							
Primary care	54	46	85%	4	7%	4	7%
Mixed	20	11	55%	7	35%	2	10%
NS	1	–		–		1	100%
Clinical setting							
Hospital-based	17	13	76%	2	12%	2	12%
Non-hospital-based	34	26	76%	5	15%	3	9%
Mixed	16	13	81%	3	19%	–	–
NS	8	5	63%	1	13%	2	25%
Ownership							
For profit	13	8	62%	2	15%	3	23%
Not for profit	30	25	83%	3	10%	2	7%
Public	11	9	82%	2	18%	–	–
Mixed	15	11	73%	4	27%	–	–
NS	6	4	67%	–	–	2	33%
Region							
Northeast	26	17	65%	4	15%	5	19%
South	13	11	85%	2	15%	–	–
Midwest	14	14	100%	–	–	–	–
West	7	4	57%	2	29%	1	14%
National	11	10	91%	1	9%	–	–
Outside US	4	1	25%	2	50%	1	25%
Intervention							
CDS[a]	35	31	89%	4	11%	–	–
Care reminders	21	21	100%	–	–	–	–
Antibiotic ordering support	5	3	60%	2	40%	–	–
Condition-specific order sets	4	3	75%	1	25%	–	–
Formulary checking	2	–	–	2	100%	–	–
Problem list management	2	2	100%	–	–	–	–
Condition-specific treatment protocol	1	1	100%	–	–	–	–
Critical laboratory value checking	1	1	100%	–	–	–	–
Drug-condition interaction checking	1	1	100%	–	–	–	–
Patient-specific relevant data displays	1	1	100%	–	–	–	–
EHR	17	15	88%	2	12%	–	–
PHR	11	10	91%	1	9%	–	–
CPOE	7	1	14%	1	14%	5	71%
CPOE with CDS[a]	2	–	–	–	–	2	100%
Drug-allergy interaction checking	2	–	–	–	–	2	100%
Drug-drug interaction checking	2	–	–	–	–	2	100%
Drug-condition interaction checking	1	–	–	–	–	1	50%
Medication dose adjustment	1	–	–	–	–	1	100%
HIE	3	–	–	3	100%	–	–
Non-ambulatory settings							
Size							
Small (<100 beds)	1	–	–	–	–	1	100%
Medium (100–399 beds)	13	4	31%	3	23%	6	46%
Large (⩾400 beds)	42	22	52%	6	14%	14	33%
Mixed	21	13	62%	5	24%	3	14%
NS	2	2	100%	–	–	–	–
Teaching status							
Academic hospital	58	26	45%	11	19%	21	36%
Non-academic hospital	7	4	57%	2	29%	1	14%
Mixed	13	10	77%	1	8%	2	15%
NS	1	1	100%	–	–	–	–
Ownership							
For profit	12	5	42%	4	33%	3	25%
Not for profit	32	15	47%	7	22%	10	31%
Public	22	11	50%	1	5%	10	45%
Mixed	12	9	75%	2	17%	1	8%
NS	1	1	100%	–	–	–	–
Region							
Northeast	11	5	45%	–	–	6	55%
South	19	12	63%	3	16%	4	21%
Midwest	15	8	53%	4	27%	3	20%
West	10	4	40%	5	50%	1	10%
National	12	9	75%	1	8%	2	17%
Outside US	12	3	25%	1	8%	8	67%
Intervention							
CDS[a]	30	21	70%	3	10%	6	20%

(*continued on next page*)

Table 1 (*continued*)

	All studies	Quality of care	%	Productivity	%	Patient safety	%
Condition-specific order sets	5	5	100%	–	–	–	–
Medication dose adjustment	5	2	40%	–	–	3	60%
Risk assessment tools	5	5	100%	–	–	–	–
Antibiotic ordering support	4	4	100%	–	–	–	–
Care reminders	3	3	100%	–	–	–	–
Critical laboratory value checking	3	2	67%	–	–	1	33%
Drug–drug interaction checking	2	–	–	–	–	2	100%
High-risk state monitoring	2	2	100%	–	–	–	–
Patient-specific relevant data displays	2	–	–	2	100%	–	–
Condition-specific treatment protocol	1	1	100%	–	–	–	–
Default doses/pick lists	1	–	–	–	–	1	100%
Formulary checking	1	–	–	1	100%	–	–
EHR	18	12	67%	6	33%	–	–
CPOE	15	3	20%	3	20%	9	60%
CPOE with CDS[a]	10	2	20%	–	–	8	80%
Medication dose adjustment	5	1	20%	–	–	4	80%
Drug–drug interaction checking	3	–	–	–	–	3	100%
Drug–condition interaction checking	2	–	–	–	–	2	100%
Antibiotic ordering support	1	1	100%	–	–	–	–
High-risk state monitoring	1	–	–	–	–	1	100%
Maximum daily dose checking	1	–	–	–	–	1	100%
Risk assessment tools	1	1	100%	–	–	–	–
Wrong patient checking[b]	1	–	–	–	–	1	100%
PHR	3	2	67%	1	33%	–	–
HIE	1	–	–	1	100%	–	–
Other	2	1	50%	–	–	1	50%

Abbreviations: NS: not specified; CDS: clinical decision support; EHR: electronic health records; CPOE: computerized provider order entry; PHR: personal health records; HIE: health information exchange.

Note: Studies were classified into more than one type of setting and dimension of care.

[a] CDS and CPOE with CDS studies were classified into more than one type of CDS.

[b] Wrong patient checking is not included in the original taxonomy created by Wright et al. [23].

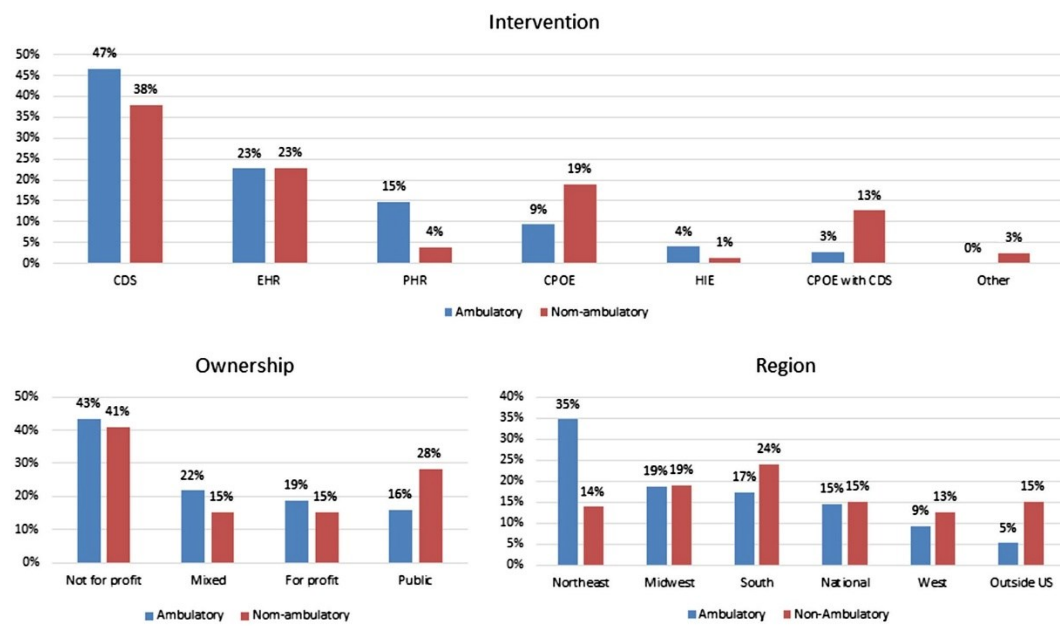

Fig. 5. Distribution of intervention, ownership and region of the studies per type of setting.

interventions. Virtually no study testing EHRs described the components involved in the intervention, while examination of CDS studies allowed for the identification of 17 distinct CDS tools. This finding demonstrates how specific IT interventions can be. The importance of a more detailed description of IT interventions for generalizability purposes had already been described by Miller [32] in 1996; however, several years later current research has still not filled this gap.

Our analysis of settings indicates that over half of ambulatory studies are conducted in non-hospital-based clinics. This could be

Table 2
Quality of care measures in ambulatory settings.

# Studies	Taxa	Measure	Description	HEDIS equivalent
Ambulatory settings - quality of care				
8	5	Blood pressure control	Blood pressure control in outpatients	Controlling High Blood Pressure
7	1	Breast cancer screening	Breast cancer screening ordered as preventive care in target patients	Breast Cancer Screening
7	5	Hemoglobin A1c control	Hemoglobin A1c control in diabetic patients	Comprehensive Diabetes Care
6	1	Colorectal cancer screening	Colorectal cancer screening ordered as preventive care in target patients	Colorectal Cancer Screening
6	1	Chlamydia screening	Chlamydia screening ordered as preventive care in target patients	Chlamydia Screening in Women
6	7	Diabetes Bundle	Composite measure for diabetes care measured as compliance to all composite items	Comprehensive Diabetes Care
6	2	Dietary counseling documented	Evidence of dietary counseling documented in patient electronic health records	Weight Assessment and Counseling for Nutrition and Physical Activity for Children/Adolescents
6	1	Osteoporosis screening	Osteoporosis screening ordered as preventive care in target patients	Osteoporosis Testing in Older Women
6	2	Pneumococcal immunization documented	Evidence of pneumococcal immunization documented in patient electronic health records	Childhood Immunization Status Pneumococcal Vaccination Status for Older Adults
5	5	LDL cholesterol control	Low-density lipoprotein cholesterol control in outpatients	Not included
5	1	Nephropathy screening	Nephropathy screening ordered as preventive care in target patients	Comprehensive Diabetes Care
5	2	Aspirin use documented	Evidence of aspirin use documented in patient electronic health records	Aspirin Use and Discussion
4	1	Cholesterol screening	Cholesterol screening ordered as preventive care in target patients	Not included
4	10	Clinician satisfaction	Clinicians' satisfaction as end user of a new or updated health IT system	Not included
4	2	Exercise counseling documented	Evidence of exercise counseling documented in patient electronic health records	Weight Assessment and Counseling for Nutrition and Physical Activity for Children/Adolescents
4	2	Influenza immunization documented	Influenza immunization documented in patient electronic health records	Childhood Immunization Status Flu Vaccinations for Adults Ages 18–64; or 65 or older
4	2	Referral to specialty care documented	Evidence of referral to a specialist documented in patient electronic health records	Not included
3	1	Abdominal aortic aneurysm screening	Abdominal aortic aneurysm screening ordered as preventive care in target patients	Not included
3	3	Appropriate use of ACE inhibitor or ARB	Orders of angiotensin-converting-enzyme inhibitor or angiotensin receptor blocker drugs in compliance with guidelines	Annual Monitoring for Patients on Persistent Medications
3	3	Appropriate use of NSAID	Orders of nonsteroidal anti-inflammatory drugs in compliance with guidelines	Not included
3	1	Cervical cancer screening	Cervical cancer screening ordered as preventive care in target patients	Cervical Cancer Screening
3	1	Diabetic retinopathy screening	Diabetic retinopathy screening ordered as preventive care for diabetic patients	Comprehensive Diabetes Care
3	1	Pap smear screening	Pap smear screening ordered as preventive care in target patients	Not included
3	12	PHR usage rate	Rate of access to personal health records by patients	Not included
3	2	Smoking cessation counseling documented	Evidence of Smoking cessation counseling documented in patient electronic health records	Medical Assistance With Smoking and Tobacco Use Cessation
3	2	Treatment for depression documented	Patients with new prescription of medication for depression and/or mental health counseling documented	Not included
2	2	Appropriate treatment for children with URI	Evidence of appropriate treatment for children with upper respiratory infection in patient electronic health records	Appropriate Treatment for Children With Upper Respiratory Infection
2	3	Appropriate use of antibiotics	Orders of antibiotic drugs in compliance with guidelines	Antibiotic utilization
2	3	Appropriate use of antithrombotic	Orders of antithrombotic drugs in compliance with guidelines	Not included
2	3	Appropriate use of beta-blocker	Orders of beta-blocker drugs in compliance with guidelines	Persistence of Beta-Blocker Treatment After a Heart Attack
2	3	Appropriate use of medication for asthma	Orders of medication for asthma in compliance with guidelines	Use of Appropriate Medications for People With Asthma
2	3	Appropriate use of statin	Orders of statin drugs in compliance with guidelines	Not included
2	2	Follow-up action documented	Number of patients with follow-up action documented in patient electronic health records	Follow-Up Care for Children Prescribed ADHD Medication Follow-Up After Hospitalization for Mental Illness
2	1	Hemoglobin A1c screening	Hemoglobin A1c screening ordered as preventive care in target patients	Comprehensive Diabetes Care
2	1	Hepatitis B antibody screening	Hepatitis B antibody screening ordered as preventive care in target patients	Not included
2	3	Inappropriate use of antibiotics	Orders of antibiotic drugs not in compliance with guidelines	Not included
2	6	Obesity diagnosis documented	Number of patients with diagnosis of obesity documented in patient electronic health records	Not included
2	10	Patient satisfaction	Patients' satisfaction with care provided measured after new or updated health IT system	Not included

(*continued on next page*)

Table 2 (*continued*)

# Studies	Taxa	Measure	Description	HEDIS equivalent
2	1	Pharyngitis screening	Pharyngitis screening ordered as preventive care in target patients	Appropriate Testing for Children With Pharyngitis
2	6	Problem documented	Problem list items in compliance with guidelines	Not included
2	6	Smoking status documented	Current and changes in smoking status for active smoking patients	Not included

Note: Measures are sorted by descending order of studies.

Table 3
Quality of care measures in non-ambulatory settings.

# Studies	Taxa	Measure	Description	CMS Hospital Compare equivalent
Non-ambulatory settings - quality of care				
9	9	Hospital LOS	Length of stay of hospitalized patients	Not included
9	4	Mortality rate	Rate of patients who died during hospitalization	MORT-30-AMI; MORT-30-HF; MORT-30-PN; MORT-30-COPD; MORT-30-STK
7	3	Appropriate use of antibiotics	Orders of antibiotic drugs in compliance with guidelines	PN-6; OP-7; SCIP-Inf-2a
7	4	Venous thromboembolism rate	Rate of patients who developed venous thromboembolism	VTE-6, PSI-12
4	4	Pressure ulcer rate	Rate of patients who developed pressure ulcer during hospitalization	Not included
4	7	Hospital Quality Alliance scores	Composite score of quality of care for patients with acute myocardial infarction, heart failure, pneumonia, and surgical care [31]	Not included
3	5	Blood glucose control	Blood glucose control in inpatients	SCIP-INF-4
3	10	Clinician satisfaction	Clinicians' satisfaction as end user of a new or updated health IT system	Not included
3	4	In-hospital bleeding rate	Rate of patients who had bleeding event during hospitalization	Not included
3	10	Patient satisfaction	Patients' satisfaction with care provided measured after new or updated health IT system	HCAHPS
3	2	Pneumococcal immunization documented	Evidence of pneumococcal immunization documented in patient electronic health records	Not included
3	2	VTE prophylaxis compliance	Orders of prophylaxis for venous thromboembolism in compliance with guidelines	SCIP-VTE-2; STK-1; VTE-1; VTE-2
2	3	Appropriate use of ACE inhibitor or ARB	Orders of angiotensin-converting-enzyme inhibitor or angiotensin receptor blocker drugs in compliance with guidelines	HF-3
2	8	Hospitalization rate	Rate of patients hospitalized	Not included
2	4	Hypoglycemic events rate	Rate of events of patients with blood sugar level below the level recommended	Not included
2	9	ICU LOS	Length of stay of patients in the intensive care unit	Not included
2	8	Readmission rate	Rate of patients readmitted within 30 days of discharge	READM-30-AMI; READM-30-HF; READM-30-PN; READM-30-HIP-KNEE; READM-30-HOSP-WIDE; READM-30-COPD; READM-30-STK
2	2	Referral to specialty care documented	Evidence of referral to a specialist documented in patient electronic health records	Not included
2	4	Sepsis rate	Rate of patients who developed sepsis	Not included
2	2	Smoking cessation counseling documented	Evidence of Smoking cessation counseling documented in patient electronic health records	Not included
2	11	Time in target glucose range	Calculated time which blood sugar level was within a target level specified by guidelines	Not included

Note: Measures are sorted by descending order of studies.

the result of a steady increase in EHR adoption by office-based physicians. While Jones et al. [12] concluded that most studies present positive results, our findings suggest that academic hospitals, which are the setting of approximately three quarters of studies in non-ambulatory settings, may be the settings where positive results are most commonly found. However, future research is necessary to confirm this association. We have identified and classified settings and interventions, and provide a set of characteristics of these protocol components that can help researchers standardize and share such information in future studies.

Previous studies have shown that the quality of care in the US presents opportunities for improvement [33], which could have contributed to an expectation that research on health IT adoption should primarily focus on quality of care. This study indicates that quality of care is by far the most common category of measurements used by researchers. Performance measures required by HEDIS readily provide the data needed to calculate more than half of the measures of quality in ambulatory settings, and Hospital Compare provides the data needed to calculate 38% of the measures of quality in non-ambulatory settings.

Patient safety studies focused exclusively on medication processes, and none of the measures used by researchers corresponds with the national reporting systems assessed. However, Hospital Compare in particular has several measures of safety-related pro-

Table 4
Patient safety and productivity measures.

# Studies	Taxa	Measure	Description	CMS Hospital Compare equivalent
Ambulatory settings - patient safety				
6	15	Medication errors	Preventable or non-preventable medication errors that did or did not reach patients	Not included
2	15	ADEs rate	Rate of adverse drug events	Not included
Non-ambulatory settings - patient safety				
14	15	Medication errors	Preventable or non-preventable medication errors that did or did not reach patients	Not included
4	15	Medication orders changed	Number of medication orders changed following clinical decision support recommendation	Not included
4	15	ADEs rate	Rate of adverse drug events	Not included
2	15	Non-recommended medications ordered	Number of medication orders not in compliance with guidelines	Not included
Ambulatory settings – productivity				
5	14	Radiology orders	Number of orders of imaging tests	
5	14	Laboratory orders	Number of orders of laboratory tests	
4	14	Medication orders	Number of orders of medication	
3	13	Patient visits	Number of patient visits to ambulatory settings	
2	13	After-hours patient calls	Number of patient calls after work hours	
Non-ambulatory settings – productivity				
6	13	ED LOS	Length of stay of patients in emergency departments	
6	13	ED visits	Number of patient visits to emergency departments	
5	14	Laboratory orders	Number of orders of laboratory tests	
3	14	Medication orders	Number of orders of medication	
3	14	Radiology orders	Number of orders of imaging tests	
2	13	Hospitalization rate	Rate of patients hospitalized	

Note: Measures are sorted by descending order of studies.

cesses [25]. Jones et al. [12] classified their safety studies using the Agency for Healthcare Research and Quality (AHRQ) safety areas recommended for future research [34], which includes universal protocol for surgical procedures; medication reconciliation; CPOE with CDS; falls prevention; and blood stream infection. Although quality is the primary focus of researchers, we assessed 31 studies of patient safety, and despite the AHRQ recommendations, the safety studies we evaluated focused exclusively on medications.

Productivity measures assess primarily the volume of medical orders and health care utilization. The inherent complexity of the non-ambulatory setting has not been widely investigated because in most studies researchers assessed only emergency departments.

Overall, the use of measures varies according to three factors: type of setting; IT intervention; and targeted population. Each study contributed, on average, 0.5 measures to the total of 79 most commonly used measures, which is a modest contribution to the spectrum of processes that can be impacted by IT interventions in health care. In addition, few measures are widely used across studies, complicating comparison of outcomes between studies. The present study contributes to filling this gap by proposing a taxonomy that can facilitate the classification and comparison of outcome measures used in future studies. The taxonomy is currently being used to identify measures for monitoring the implementation of a commercial EHR at Intermountain Healthcare. We expect to report our experience with the use of the taxonomy and the implementation process in future studies.

4.1. Implications for future research

We identified several aspects of the current literature that can be further explored in future studies. A more robust and standardized measurement system that is shared among researchers is necessary to facilitate comparison of outcomes between studies. More detailed and standardized descriptions of settings and interventions are also necessary to facilitate such a comparison. We speculate that data available in common reporting systems may influence the choice of specific measures by researchers and suggest future research to assess this hypothesis. Patient safety studies commonly focus on medications; other safety areas recommended by the AHRQ are underexplored and should be considered for future research. Finally, several studies assess individual departments such as emergency departments; the inherent complexity of health care systems warrants wider organizational investigation.

4.2. Limitations

Our study has several limitations. A single reviewer first evaluated and classified the articles and measures. To minimize the potential for data misclassification, several iterations of article and measure classification were performed. Even though we contacted corresponding authors and searched the web for missing information, in some cases we were not able to find needed information for a complete analysis. Articles included in a previously published systematic review were used instead of conducting a new review; such an approach has potential for publication bias inherent in the previous review; it also may have limited the identification of measures and taxa. We intend to address the latter by eliciting more measures from experts at Intermountain Healthcare and report our results in a future study. Lastly, we included only HEDIS and Hospital Compare reporting systems in our analysis; nevertheless, they are widely adopted and well known to researchers and health care providers.

5. Conclusions

Research on health IT adoption commonly explores quality of care outcomes primarily obtained from clinical decision support systems implemented in large academic hospitals and non-hospital-based clinics. Studies involving EHRs rarely provide a detailed description of EHR components tested. Although measures used vary substantially, often only a small set of measures is utilized in each study. In the area of patient safety, researchers explore exclusively medication processes while productivity focuses on volume of medical orders and health care utilization. Only a few measures have been widely used, and measures of quality tend to be ones for which data are available in reporting systems. We provide a taxonomy of commonly used measures that can help researchers identify measures and fill gaps in their measurement approaches. Future research can improve our understanding of the impact of health IT adoption with a more robust measurement system and detailed descriptions of interventions and settings.

Conflict of interest

None declared.

Acknowledgements

The authors would like to acknowledge Spencer S. Jones, Ph.D., for sharing additional material of the original systematic review used in our analysis. We would also like to acknowledge the authors who provided additional information on their studies: Donald P. Connelly, M.D., Ph.D.; Eric Eisenstein, DBA; Ofir Ben-Assuli; Ted E. Palen, Ph.D., M.D., MSPH; Michael Yaron, M.D.; Jennifer Walker, MPH, Ph.D.; Sameer Malhotra, MD, M.A.; Jeffrey N. Epstein, Ph.D.; and Cara Litvin MD, M.S. This research was supported by Intermountain Healthcare, Salt Lake City, UT, USA. JCF has been partially supported by the National Center for Advancing Translational Sciences of the National Institutes of Health under Award Number 5UL1TR001067-03.

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.2016.07.018.

References

[1] E.L. Ciemins, P.J. Coon, J.B. Fowles, S. Min, Beyond health information technology: critical factors necessary for effective diabetes disease management, J. Diabetes Sci. Technol. 3 (3) (2009) 452–460.

[2] U. Pöder, M. Fogelberg-Dahm, B. Wadensten, Implementation of a multi-professional standardized care plan in electronic health records for the care of stroke patients, J. Nurs. Manage. 19 (6) (2011) 810–819.

[3] J. Adler-Milstein, C. Salzberg, C. Franz, E.J. Orav, J.P. Newhouse, D.W. Bates, Effect of electronic health records on health care costs: longitudinal comparative evidence from community practices, Ann. Int. Med. 159 (2) (2013) 97–104.

[4] The White House Archives <http://georgewbush-whitehouse.archives.gov/news/releases/2004/04/20040427-4.html> (accessed on 16 July 2015).

[5] HITECH Act § 13400(5).

[6] Mathematica Policy Research, Harvard School of Public Health, Robert Wood Johnson Foundation. Health Information Technology in the United States 2013: Better Information Systems for Better Care. 2013 <www.rwjf.org/en/research-publications/find-rwjf-research/2013/07/health-information-technology-in-the-united-states-2013.html> (Accessed on 12 June 2015).

[7] C.-J. Hsiao, E. Hing, et al., Use and Characteristics of Electronic Health Record Systems Among Office-based Physician Practices, United States, 2001–2012 [Internet], US Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Health Statistics, 2012 [cited 2015 Sep 29]. Available from: <http://198.246.124.22/nchs/data/databriefs/db143.pdf>.

[8] D. Charles, J. King, V. Patel, M.F. Furukawa, Adoption of Electronic Health Record Systems Among US Non-Federal Acute Care Hospitals: 2008–2012 [Internet], Office of the National Coordinator for Health Information Technology, 2013 [cited 2015 Sep 29]. Available from: <http://healthit.gov/sites/default/files/data-brief/2014HospitalAdoptionDataBrief.pdf>.

[9] B. Chaudhry, J. Wang, S. Wu, M. Maglione, W. Mojica, E. Roth, et al., Systematic review: impact of health information technology on quality, efficiency, and costs of medical care, Ann. Int. Med. 144 (10) (2006) 742–752.

[10] C.L. Goldzweig, A. Towfigh, M. Maglione, P.G. Shekelle, Costs and benefits of health information technology: new trends from the literature, Health Aff. 28 (2) (2009) w282–w293.

[11] M.B. Buntin, M.F. Burke, M.C. Hoaglin, D. Blumenthal, The benefits of health information technology: a review of the recent literature shows predominantly positive results, Health Aff. 30 (3) (2011) 464–471.

[12] S.S. Jones, R.S. Rudin, T. Perry, P.G. Shekelle, Health information technology: an updated systematic review with a focus on meaningful use, Ann. Int. Med. 160 (1) (2014 Jan 7) 48–54.

[13] J.L. Schnipper, T.K. Gandhi, J.S. Wald, R.W. Grant, E.G. Poon, L.A. Volk, et al., Effects of an online personal health record on medication accuracy and safety: a cluster-randomized trial, J. Am. Med. Inf. Assoc. 19 (5) (2012) 728–734.

[14] D.P. Connelly, Y.-T. Park, J. Du, N. Theera-Ampornpunt, B.D. Gordon, B.A. Bershow, et al., The impact of electronic health records on care of heart failure patients in the emergency room, J. Am. Med. Inf. Assoc. 19 (3) (2012) 334–340.

[15] K.M. Nazi, Veterans' voices: use of the American Customer Satisfaction Index (ACSI) Survey to identify My HealtheVet personal health record users' characteristics, needs, and preferences, J. Am. Med. Inf. Assoc. 17 (2) (2010) 203–211.

[16] P.L.T. Hoonakker, P. Carayon, R.L. Brown, R.S. Cartmill, T.B. Wetterneck, J.M. Walker, Changes in end-user satisfaction with Computerized Provider Order Entry over time among nurses and providers in intensive care units, J. Am. Med. Inf. Assoc. 20 (2) (2013 Mar 1) 252–259.

[17] G.W. Roberts, C.J. Farmer, P.C. Cheney, S.M. Govis, T.W. Belcher, S.A. Walsh, et al., Clinical decision support implemented with academic detailing improves prescribing of key renally cleared drugs in the hospital setting, J. Am. Med. Inf. Assoc. 17 (3) (2010) 308–312.

[18] T.E. Klatt, E. Hopp, Effect of a best-practice alert on the rate of influenza vaccination of pregnant women, Obstet. Gynecol. 119 (2, Part 1) (2012) 301–305.

[19] H. Singh, E.J. Thomas, D.F. Sittig, L. Wilson, D. Espadas, M.M. Khan, et al., Notification of abnormal lab test results in an electronic medical record: do any safety concerns remain?, Am J. Med. 123 (3) (2010) 238–244.

[20] R. Penfold, F. Zhang, S. Soumerai, Impact of electronic health record transition on behavioral health screening, Psych. Serv. 63 (3) (2012) 256–261.

[21] UpToDate <http://www.uptodate.com/home> (accessed from June 01to June 30, 2015).

[22] The Unified Medical Language System <https://uts.nlm.nih.gov/home.html> (accessed from June 01to June 30, 2015).

[23] A. Wright, D.F. Sittig, J.S. Ash, J. Feblowitz, S. Meltzer, C. McMullen, et al., Development and evaluation of a comprehensive clinical decision support taxonomy: comparison of front-end tools in commercial and internally developed electronic health record systems, J. Am. Med. Inf. Assoc. 18 (3) (2011) 232–242.

[24] The National Committee for Quality Assurance HEDIS Measures 2015 <http://www.ncqa.org/Portals/0/HEDISQM/Hedis2015/List_of_HEDIS_2015_Measures.pdf> (accessed 30 June 2015).

[25] CMS Hospital Compare Data Archive <https://data.medicare.gov/data/archives/hospital-compare> (Accessed 30 June 2015).

[26] G. Sanfélix-Gimeno, J.M. Franklin, W.H. Shrank, M. Carlo, A.Y. Tong, L. Reisman, et al., Did HEDIS get it right? Evaluating the quality of a quality measure: adherence to β-blockers and cardiovascular outcomes after myocardial infarction, Med. Care 52 (7) (2014) 669–676.

[27] S.P. Schmaltz, S.C. Williams, M.R. Chassin, J.M. Loeb, R.M. Wachter, Hospital performance trends on national quality measures and the association with joint commission accreditation, J. Hosp. Med. 6 (8) (2011 Oct) 454–461.

[28] The Leapfrog Safe Hospital Safety Score <http://www.hospitalsafetyscore.org/media/file/HospitalSafetyScore_ScoringMethodology_Spring2015_Final.pdf> (accessed on 30 June 2015).

[29] e-CFR: Title 45: Public Welfare [Internet]. Electronic Code of Federal Regulations. Sect. Part 170—Health Information Technology Standards, Implementation Specifications, and Certification Criteria and Certification Programs for Health Information Technology <http://www.ecfr.gov/cgi-bin/text-idx?SID=7864fe0ec2f5a722c328b71bbffb68ff&mc=true&node=pt45.1.170&rgn=div5> (accessed on 12 June 2015).

[30] The American Hospital Directory <https://www.ahd.com/search.php> (accessed from June 01 to June 30, 2015).

[31] A.K. Jha, Z. Li, E.J. Orav, A.M. Epstein, Care in U.S. hospitals – the hospital quality alliance program, N. Engl. J. Med. 353 (3) (2005) 265–274.

[32] R.A. Miller, Evaluating evaluations of medical diagnostic systems, J. Am. Med. Inf. Assoc. 3 (6) (1996) 429–431.

[33] E.A. McGlynn, S.M. Asch, J. Adams, J. Keesey, J. Hicks, A. DeCristofaro, et al., The quality of health care delivered to adults in the United States, N. Engl. J. Med. 348 (26) (2003) 2635–2645.

[34] P.G. Shekelle, P.J. Pronovost, R.M. Wachter, S.L. Taylor, S. Dy, R. Foy, et al., PSP Technical Expert Panel. Assessing the Evidence for Context-Sensitive Effectiveness and Safety of Patient Safety Practices: Developing Criteria (Prepared under Contract no. HHSA-290-2009-10001C). AHRQ Publication No. 11-0006-EF, Agency for Healthcare Research and Quality, Rockville, MD, 2010 (December).

3.8 Supplementary Materials

Table 3S.1. Quality of care in ambulatory settings

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Abdel, et a. 2012(35)	Appropriate use of ACE inhibitor or ARB Appropriate use of NSAID Nephropathy screening Referral to Specialty Care documented Blood pressure control	Northeast	Primary Care	Hospital-based	For profit	CDS - Care reminders
Atlas, et al. 2011(36)	Breast cancer screening	Northeast	Primary Care	Hospital-based	Not for profit	EHR
Bell, et al. 2012(37)	Appropriate use of medication for asthma	Northeast	Primary Care	NS	NS	CDS - Care reminders
Bian, et al. 2012(38)	Colorectal cancer screening	South	Primary Care	Mixed	Public	CDS - Care reminders
Bourgeois, et al. 2010(39)	Appropriate use of antibiotics	Northeast	Primary Care	Mixed	Mixed	CDS - Antibiotic ordering support
Carroll, et al. 2012(40)	Referral to Specialty Care documented	Midwest	Primary Care	NS	NS	CDS - Care reminders
Cebul, et al. 2011(41)	Diabetes Bundle (A1c, BP, LDL or statin, BMI, nonsmoking status) Diabetes Bundle (A1c, Microalbuminuria or ACEi or ARB, Diabetic Retinopathy Screening, pneumococcal vaccination)	Midwest	Primary Care	Mixed	Not for profit	EHR

Table 3S.1. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Chaudhry, et al. 2011(42)	Abdominal aortic aneurysm screening	Midwest	Primary Care	NS	Not for profit	CDS - Care reminders
Coleman, et al. 2012(43)	Dietary counseling documented Obesity diagnosis documented	West	Primary Care	Non-hospital-based	Not for profit	CDS - Care reminders
Crosson, et al. 2012(44)	Diabetes Bundle (A1c, BP, LDL, Nephropathy screening, nonsmoking status)	Northeast	Primary Care	Non-hospital-based	Not for profit	EHR
Davis, et al. 2010(45)	Appropriate use of inhaled corticosteroid	South	Primary Care	Hospital-based	Not for profit	EHR
Dejesus, et al. 2010(46)	Osteoporosis screening	Midwest	Primary Care	Non-hospital-based	Not for profit	CDS - Care reminders
Delbanco, et al. 2012(47)	PHR usage rate Patient satisfaction	National	Primary Care	Mixed	Mixed	PHR
Dufft, et al. 2010(48)	Clinician satisfaction Patient satisfaction Patient visits After-hours patient calls	South	Primary Care	Non-hospital-based	Public	CPOE
Eaton, et al. 2012(49)	Abdominal aortic aneurysm screening	Midwest	Primary Care	Hospital-based	Not for profit	CDS - Care reminders
El-Kareh, et al. 2012(50)	Clinician satisfaction Follow-up action documented	Northeast	Mixed	Hospital-based	Not for profit	EHR
Epstein, et al. 2011(51)	PHR usage rate	South	Primary Care	Mixed	Mixed	PHR
Feblowitz, et al. 2013(52)	Clinician satisfaction Problem documented	Northeast	Primary Care	Hospital-based	Not for profit	CDS - Problem list management

Table 3S.1. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Feldstein, et al. 2010(53)	Diabetes Bundle (A1c, LDL, ACE inhibitor, Statin, Diabetic Retinopathy Screening)	West	Primary Care	Non-hospital-based	Not for profit	CDS - Care reminders
Frimpong, et al. 2013(54)	Referral to Specialty Care documented	National	Primary Care	Mixed	Not for profit	EHR
Gill, et al. 2011(55)	Appropriate use of NSAID	National	Primary Care	Mixed	Mixed	CDS - Drug–condition interaction checking
Harman, et al. 2012(56)	Treatment of depression documented	National	Primary Care	Non-hospital-based	Mixed	EHR
Herrin, et al. 2012(57)	Diabetes Bundle (A1c, BP, LDL, Aspirin use, nonsmoking status)	South	Primary Care	Non-hospital-based	Not for profit	EHR
Hsu, et al. 2012(58)	Hepatitis B antibody screening	West	Primary Care	Non-hospital-based	For profit	CDS - Care reminders
Keeubauch, et al. 2012(59)	Dietary counseling documented Exercise counseling Cholesterol screening Follow-up action documented	South	Primary Care	Non-hospital-based	Not for profit	EHR
Kern, et al. 2013(60)	Breast cancer screening Chlamydia screening Colorectal cancer screening Hemoglobin A1c control LDL cholesterol control Appropriate use of medication for asthma	Northeast	Primary Care	Non-hospital-based	Not for profit	EHR

Table 3S.1. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Kesman, et al. 2010(61)	Osteoporosis screening	Midwest	Primary Care	Non-hospital-based	Not for profit	CDS - Care reminders
Krist, et al. 2012(62)	Breast cancer screening Chlamydia screening Dietary counseling documented Osteoporosis screening Pneumococcal immunization documented Abdominal aortic aneurysm screening Aspirin use documented Cervical cancer screening Cholesterol screening Exercise counseling Influenza immunization documented PHR usage rate Smoking cessation counseling documented	South	Primary Care	Non-hospital-based	For profit	PHR
Lapham, et al. 2012(63)	Referral to specialty care documented	National	Mixed	Hospital-based	Public	CDS - Care reminders
Litvin, et al. 2013(64)	Inappropriate use of antibiotics	National	Primary Care	Non-hospital-based	For profit	CDS - Antibiotic ordering support
Loo, et al. 2011(65)	Osteoporosis screening Pneumococcal immunization documented	Northeast	Primary Care	Hospital-based	For profit	CDS - Care reminders

Table 3S.1. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Mainous, et al. 2012(66)	Inappropriate use of antibiotics	National	Primary Care	NS	NS	CDS - Antibiotic ordering support
Mathias, et al. 2012(67)	Smoking cessation counseling documented Smoking status documented	Midwest	Primary Care	Non-hospital-based	For profit	CDS - Condition-specific order sets
McCullough, et al. 2013(68)	Diabetes Bundle (A1c, BP, LDL, Aspirin use, nonsmoking status)	Midwest	Mixed	Mixed	Mixed	EHR
Nagykaldi, et al. 2012(69)	Pneumococcal immunization documented Aspirin use documented	South	Primary Care	Non-hospital-based	Public	PHR
O'Connor, et al. 2011(70)	Blood pressure control Hemoglobin A1c control LDL cholesterol control	Midwest	Primary Care	Non-hospital-based	Not for profit	CDS - Condition-specific treatment protocol
Persell, et al. 2011(71)	Colorectal cancer screening Hemoglobin A1c control LDL cholesterol control Osteoporosis screening Pneumococcal immunization documented Appropriate use of ACE inhibitor or ARB Appropriate use of antithrombotic Appropriate use of beta-blocker	Midwest	Primary Care	Non-hospital-based	Not for profit	CDS - Care reminders

Table 3S.1. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Poon, et al. 2010(72)	Diabetes Bundle (A1c, LDL, Nephropathy screening, Diabetic Retinopathy Screening) Colorectal cancer screening	Northeast	Primary Care	Mixed	Mixed	EHR
Quinn, et al. 2011(73)	Blood pressure control Hemoglobin A1c control LDL cholesterol control	South	Primary Care	Non-hospital-based	Not for profit	PHR
Riley, et al. 2010(74)	Chlamydia screening Hepatitis B antibody screening Pap smear	Midwest	Primary Care	Non-hospital-based	Public	CDS - Care reminders
Romano & Stafford, 2011(75)	Blood pressure control Dietary counseling documented Appropriate use of ACE inhibitor or ARB Appropriate use of antibiotics Appropriate use of antithrombotic Appropriate use of beta-blocker Appropriate use of statin Aspirin use documented Exercise counseling documented Appropriate use of inhaled corticosteroid	National	Mixed	Mixed	Mixed	CDS - Care reminders

Table 3S.1. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Ryan, et al. 2013(76)	Breast cancer screening Chlamydia screening Colorectal cancer screening Cervical cancer screening Cholesterol screening Diabetic Retinopathy screening Hemoglobin A1c screening Nephropathy screening Pharyngitis screening	Northeast	Mixed	Mixed	Public	EHR
Samal, et al. 2010(77)	Blood pressure control	National	Mixed	Non-hospital-based	Mixed	CDS - Care reminders
Sequist, et al. 2011(78)	Colorectal cancer screening	Northeast	Mixed	Non-hospital-based	Not for profit	PHR
Sequist, et al. 2012(79)	Aspirin use documented	Northeast	Primary Care	Non-hospital-based	Not for profit	CDS - Care reminders
Shelley, et al. 2011(80)	Blood pressure control	Northeast	Primary Care	Non-hospital-based	Not for profit	CDS - Care reminders Patient-specific relevant data displays Condition-specific order sets
Singh, et al. 2010(81)	Hemoglobin A1c control	South	Mixed	Hospital-based	Public	CDS - Critical laboratory value checking
Tang, et al. 2012(82)	Hemoglobin A1c control	West	Mixed	Mixed	Not for profit	PHR

Table 3S.1. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Tang, et al. 2012(83)	Dietary counseling documented Obesity diagnosis documented	Midwest	Primary Care	Non-hospital-based	For profit	CDS - Condition-specific order sets
Tenforde, et al. 2012(84)	Blood pressure control Hemoglobin A1c control LDL cholesterol control Pneumococcal immunization documented Diabetic Retinopathy screening Hemoglobin A1c screening Nephropathy screening Smoking status documented	Midwest	Primary Care	Hospital-based	For profit	PHR
Tundia, et al. 2012(85)	Chlamydia screening Dietary counseling documented Osteoporosis screening Cholesterol screening Exercise counseling Influenza immunization documented Breast cancer screening Pap smear	National	Mixed	Non-hospital-based	Mixed	EHR
Wagner, et al. 2012(86)	Blood pressure control	South	Primary Care	Hospital-based	Public	PHR

Table 3S.1. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Walker, et al. 2010(87)	Chlamydia screening	Outside US	Primary Care	Non-hospital-based	Mixed	CDS - Care reminders
Williams, et al. 2011(88)	Treatment of depression documented	Midwest	Primary Care	Hospital-based	Public	CDS - Care reminders
Wright, et al. 2012(89)	Pneumococcal immunization documented Cholesterol screening Influenza immunization documented Breast cancer screening Pap smear	Northeast	Primary Care	Mixed	Not for profit	PHR
Wright, et al. 2012(90)	Problem documented	Northeast	Primary Care	Hospital-based	Not for profit	CDS - Problem list management
Zandieh, et al. 2011(91)	Clinician satisfaction	Northeast	Mixed	NS	NS	EHR

Table 3S.2. Quality of care in nonambulatory settings

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Appari, et al. 2012(92)	Hospital Quality Alliance scores	National	Mixed	Mixed	Mixed	EHR
Austrian, et al. 2011(93)	Hospital LOS Mortality rate Medication orders changed	Northeast	Academic hospital	L	Not for profit	CDS - Critical laboratory value checking
Boustani, et al. 2012(94)	Referral to specialty care documented	Midwest	Academic hospital	M	Public	CDS - Care reminders
Carman, et al. 2011(95)	Appropriate use of antibiotics	South	NS	NS	For profit	CDS - Antibiotic ordering support
Cho, et al. 2013(96)	Pressure ulcer rate ICU LOS	Outside US	Academic hospital	L	Not for profit	CDS - Risk assessment tools
Cook, et al. 2011(97)	Appropriate use of antibiotics	South	Academic hospital	L	Not for profit	CPOE with CDS - Antibiotic ordering support
Conelly, et al. 2012(98)	ED LOS Laboratory orders Medication orders Radiology orders Hospital LOS Mortality rate Hospitalization rate	Midwest	Academic hospital	Mixed	Not for profit	EHR
Delmonte, et al. 2012(99)	Blood glucose control	Midwest	Academic hospital	L	Public	CDS - High-risk state monitoring
Desroches, et al. 2010(100)	Hospital LOS Hospital Quality Alliance scores Mortality rate	National	Mixed	Mixed	Mixed	EHR
Dexheimer, et al. 2013(101)	Pneumococcal immunization documented	South	Academic hospital	L	For profit	CDS - Care reminders
Do, et al. 2011(102)	Patient satisfaction	West	Non-academic hospital	L	Public	PHR

Table 3S.2. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Dowding, et al. 2012(103)	Pressure ulcer rate	West	Mixed	Mixed	Not for profit	EHR
Dumont, et al. 2012(104)	Blood glucose Hypoglycemic events rate Time in target glucose range	South	Non-academic hospital	L	Not for profit	CDS - Medication dose adjustment
Fiumara, et al. 2010(105)	Venous thromboembolism rate Venous thromboembolism prophylaxis	Northeast	Academic hospital	L	Not for profit	CDS - Risk assessment tools Condition-specific order sets
Furukawa, et al. 2010(106)	Pressure ulcer Hospital LOS Mortality rate	West	Mixed	M	Mixed	EHR
Galanter, et al. 2010(107)	Venous thromboembolism rate In-hospital bleeding rate	Midwest	Academic hospital	L	Public	CDS - Risk assessment Condition-specific order sets
Gerra, et al. 2010(108)	Blood glucose control	Midwest	Academic hospital	L	Not for profit	CDS - Medication dose adjustment
Haut, et al. 2012(109)	Venous thromboembolism rate Venous thromboembolism prophylaxis	South	Academic hospital	L	Not for profit	CDS - Risk assessment tools Condition-specific order sets
Himmelstein, et al 2010(110)	Hospital Quality Alliance scores	National	Mixed	Mixed	Mixed	EHR
Hoekstra, et al. 2010(111)	Clinician satisfaction	Outside US	Academic hospital	L	Public	CDS - Critical lab value checking
Holden, et al. 2012(112)	Clinician satisfaction	Midwest	Academic hospital	M	Not for profit	BCMA
Hoonakker, et al. 2012(113)	Clinician satisfaction	Northeast	Academic hospital	L	Public	CPOE

Table 3S.2. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Jones, et al. 2010(114)	Hospital Quality Alliance scores	National	Mixed	Mixed	Mixed	EHR
Jones, et al. 2011(115)	Mortality rate	National	Mixed	Mixed	Mixed	CPOE
Kazley, et al. 2012(116)	Patient satisfaction	National	Mixed	Mixed	Mixed	EHR
Lee, et al. 2013(117)	Hospital LOS Mortality rate Readmission rate	National	Mixed	Mixed	Mixed	EHR
Mann, et al. 2011(118)	Hypoglycemic events rate Time in target glucose range	South	Non-academic hospital	L	Public	CDS - Critical laboratory value checking
McCluggage, et al. 2010(119)	Appropriate use of antibiotics	South	Academic hospital	L	Public	CDS - Antibiotic ordering support
McCullough, et al. 2010(120)	Appropriate use of antibiotics Appropriate use of ACE inhibitor or ARB Pneumococcal immunization documented Smoking cessation counseling documented	National	Mixed	Mixed	Mixed	EHR
Milani, et al. 2012(121)	Hospital LOS Appropriate use of ACE or ARB Referral to specialty care Smoking cessation counseling	South	Academic hospital	L	For profit	CDS - Condition-specific order sets
Milani, et al.2011(122)	In-hospital bleeding rate	South	Academic hospital	L	For profit	CPOE with CDS - Medication dose adjustment Risk assessment tools

Table 3S.2. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Moore, et al. 2010(123)	Mortality rate Sepsis rate	South	Academic hospital	L	Not for profit	CDS - Condition-specific protocol
Nazi KM, 2010(124)	Patient satisfaction	National	Non-academic hospital	Mixed	Public	PHR
Schenarts, et al. 2012(125)	Pressure ulcer rate Hospital LOS Mortality rate ICU LOS Venous thromboembolism Sepsis rate	South	Academic hospital	NS	NS	EHR
Schwann, et al. 2011(126)	Appropriate use of antibiotics	Northeast	Academic hospital	L	Not for profit	CDS - Antibiotic ordering support
Speedie, et al. 2013(127)	ED LOS Laboratory orders Medication orders Radiology orders Hospital LOS Mortality rate Hospitalization rate	Midwest	Academic hospital	Mixed	Not for profit	EHR
Swenson, et al. 2012(128)	Pneumococcal immunization documented	West	Academic hospital	L	Not for profit	CDS - Care reminders
Umscheid, et al. 2012(129)	Venous thromboembolism Venous thromboembolism prophylaxis In-hospital bleeding rate	Northeast	Academic hospital	Mixed	For profit	CDS - Risk assessment tools Condition-specific order sets
Westphal, et al. 2011(130)	Appropriate use of antibiotics	Outside US	Academic hospital	L	Public	CDS - Antibiotic ordering
Zlabek, et al. 2010(131)	Medication errors Laboratory orders Radiology orders Hospital LOS Readmission rate	Midwest	Academic hospital	M	Not for profit	CPOE
Traugott, et al. 2011(158)	Appropriate use of antibiotics	South	Academic hospital	L	Public	CDS - High-risk state monitoring

Table 3S.3. Patient safety in ambulatory settings

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Abramson, et al. 2011(132)	Medication errors	Northeast	NS	NS	NS	CPOE with CDS - Drug-drug interaction; Drug-allergy interaction
Abramson, et al. 2011(133)	Medication errors	Northeast	Primary Care	Hospital-based	NS	CPOE
Allen, et al. 2012(134)	Medication errors ADEs rate	Northeast	Primary Care	Non-hospital-based	Not for profit	CPOE
Dainty, et al. 2011(135)	Medication errors	Outside US	Mixed	Hospital-based	For profit	CPOE
Devine, et al. 2010(136)	ADEs rate	West	Mixed	Non-hospital-based	For profit	CPOE
Kaushal, et al. 2011(137)	Medication errors	Northeast	Primary Care	Non-hospital-based	Not for profit	CPOE with CDS - Drug-drug interaction; Drug-allergy interaction; Drug–condition interaction checking; Medication dose adjustment
Moniz, et al. 2011(138)	Medication errors	Northeast	Primary Care	NS	For profit	CPOE

Table 3S.4. Patient safety in nonambulatory settings

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Austrian, et al. 2011(93)	Hospital LOS Mortality rate Medication orders changed	Northeast	Academic hospital	L	Not for profit	CDS - Critical laboratory value checking
Zlabek, et al. 2010(131)	Medication errors Laboratory orders Radiology orders Hospital LOS Readmission rate	Midwest	Academic hospital	M	Not for profit	CPOE
Abdel-Qader, et al. 2010(139)	Medication errors	Outside US	Academic hospital	L	Public	Medication Orders Report
Adelman, et al. 2012(140)	Medication errors	Northeast	Academic hospital	L	Not for profit	CPOE with CDS - Wrong patient check
Ali, et al. 2010(141)	Medication errors	Outside US	Academic hospital	S	Public	CPOE
Chen, et al. 2011(142)	Medication errors	South	Academic hospital	L	Not for profit	CPOE
Chen, et al. 2011(143)	Medication errors	South	Academic hospital	L	Not for profit	CPOE
Daniels, et al. 2012(144)	Medication errors	South	Academic hospital	L	Not for profit	CDS - Drug-drug interaction; Default doses/pick lists
Galanter, et al. 2013(145)	Medication errors	Midwest	Academic hospital	L	Public	CPOE
Leung, et al. 2012(146)	ADEs rate	Northeast	Academic hospital	M	Not for profit	CPOE

Table 3S.4. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Mattison, et al. 2010(147)	Nonrecommended medications ordered	Northeast	Academic hospital	L	For profit	CPOE with CDS - Medication dose adjustment; Drug–condition interaction checking
McCoy, et al. 2010(148)	Medication orders changed	South	Academic hospital	L	Not for profit	CPOE with CDS - Medication dose adjustment
Metzger, et al. 2010(149)	ADEs rate	National	Mixed	Mixed	Mixed	CPOE with CDS - Medication dose adjustment; Maximum daily dose checking; Drug–condition interaction checking; High-risk state monitoring
Miller, et al. 2011(150)	ADEs rate	West	Non-academic hospital	M	Public	CDS - Drug–drug interaction checking
Roberts, et al. 2010(151)	Medication errors	Outside US	Academic hospital	M	Public	CDS - Medication dose adjustment
Roberts, et al. 2010(152)	ADEs rate	National	Mixed	M	Not for profit	CPOE with CDS - Drug-drug interaction
Seidling, et al. 2010(153)	Medication errors	Outside US	Academic hospital	L	Public	CDS - Medication dose adjustment

Table 3S.4. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Strom, et al. 2010(154)	Medication orders changed	Northeast	Academic hospital	M	For profit	CPOE with CDS - Drug-drug interaction
Strom, et al. 2010(155)	Nonrecommended medications ordered	Northeast	Academic hospital	L	For profit	CPOE with CDS - Drug-drug interaction
Taegtme, et al. 2011(156)	Medication orders changed	Outside US	Academic hospital	L	Public	CPOE
Terrell, et al. 2010(157)	Medication errors	Midwest	Academic hospital	L	Public	CDS - Medication dose adjustment
Wang, et al. 2012(159)	Medication errors	Outside US	Academic hospital	L	Not for profit	CPOE with CDS - Medication dose adjustment
Westbrook, et al. 2012(160)	Medication errors	Outside US	Academic hospital	Mixed	Public	CPOE
Westbrook, et al. 2012(161)	Medication errors	Outside US	Academic hospital	Mixed	Public	CPOE

Table 3S.5. Productivity in ambulatory settings

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Duffy, et al. 2010(48)	Clinician satisfaction Patient satisfaction Patient visits After-hours patient calls	South	Primary Care	Non-hospital-based	Public	CPOE
Furukawa, et al. 2011(162)	Laboratory orders Radiology orders	National	Mixed	Non-hospital-based	Mixed	EHR
Gonzales, et al. 2013(163)	Medication orders	Northeast	Primary Care	Non-hospital-based	Not for profit	CDS - Antibiotic ordering support
Hebel, et al. 2012(164)	Laboratory orders	Northeast	Mixed	Hospital-based	Not for profit	HIE
Maenpaa, et al. 2011(165)	Laboratory orders Radiology orders Patient visits	Outside US	Mixed	NS	Public	HIE
Malhotra, et al. 2012(166)	Medication orders	Northeast	Mixed	Mixed	For profit	CDS - Formulary checking
McCormick, et al. 2012(167)	Radiology orders	Outside US	Mixed	Non-hospital-based	Mixed	EHR
McGinn, et al. 2013(168)	Medication orders Radiology orders Laboratory orders	Northeast	Primary Care	Hospital-based	Not for profit	CDS - Antibiotic ordering support Condition-specific order sets
Palen, et al. 2012(169)	Patient visits After-hours patient calls	West	Primary Care	Non-hospital-based	Mixed	PHR
Ross, et al. 2013(170)	Laboratory orders Radiology orders	West	Mixed	Mixed	Mixed	HIE
Stenner, et al. 2010(171)	Medication orders	South	Mixed	Mixed	For profit	CDS - Formulary checking

Table 3S.6. Productivity in nonambulatory settings

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Conelly, et al. 2012(98)	ED LOS Laboratory orders Medication orders Radiology orders Hospital LOS Mortality rate Hospitalization rate	Midwest	Academic Hospital	Mixed	Not for profit	EHR
Speedie, et al. 2013(127)	ED LOS Laboratory orders Medication orders Radiology orders Hospital LOS Mortality rate Hospitalization rate	Midwest	Academic Hospital	Mixed	Not for profit	EHR
Zlabek, et al. 2010(131)	Medication errors Laboratory orders Radiology orders Hospital LOS Readmission rate	Midwest	Academic hospital	M	Not for profit	CPOE
Palen, et al. 2012(169)	ED visits Hospitalization rate	West	Non-academic hospital	M	For profit	PHR
Abello, et al. 2012(172)	ED visits	South	Academic hospital	Mixed	Not for profit	CDS - Patient-specific relevant data displays
Ben-Assuli, et al. 2012(173)	ED visits	Outside US	Academic hospital	L	Not for profit	EHR
Blankeship, et at. 2012(174)	Medication orders	West	Academic hospital	L	Public	CPOE

Table 3S.6. Continued

Reference	Measures used	Region	Practice	Setting	Ownership	Intervention
Eisenstein, et al. 2012(175)	ED visits Hospitalization rate	South	Academic hospital	Mixed	Mixed	CDS - Patient-specific relevant data displays
Feldman, et el. 2013(176)	Laboratory orders	South	Academic hospital	L	Not for profit	CDS - Formulary checking
Fernando, et al. 2012(177)	ED visits	West	Academic hospital	L	For profit	HIE
Furukawa, 2011(178)	ED LOS	National	Mixed	Mixed	Mixed	EHR
Mayer, et al. 2010(179)	ED LOS	West	Academic hospital	L	For profit	EHR
Spalding, et al. 2011(180)	ED LOS	West	Academic hospital	M	For profit	CPOE
Stokes, et al. 2010(181)	ED LOS ED visits Laboratory orders	Midwest	Non-academic hospital	L	Not for profit	EHR

CHAPTER 4

DEVELOPMENT AND CLASSIFICATION OF A ROBUST INVENTORY OF NEAR REAL-TIME OUTCOME MEASUREMENTS FOR ASSESSING INFORMATION TECHNOLOGY INTERVENTIONS IN HEALTH CARE

Tiago K. Colicchio, Guilherme Del Fiol, Debra L. Scammon, Watson A. Bowes III, Julio C. Facelli, Scott P. Narus

Journal of Biomedical Informatics, Volume 73, September 2017, Pages 62-75

https://doi.org/10.1016/j.jbi.2017.07.014

Journal of Biomedical Informatics 73 (2017) 62–75

Contents lists available at ScienceDirect

Journal of Biomedical Informatics

journal homepage: www.elsevier.com/locate/yjbin

Special Communication

Development and classification of a robust inventory of near real-time outcome measurements for assessing information technology interventions in health care

Tiago K. Colicchio [a,*], Guilherme Del Fiol [a], Debra L. Scammon [b], Watson A. Bowes III [a,c], Julio C. Facelli [a], Scott P. Narus [a,c]

[a] Department of Biomedical Informatics, University of Utah, Salt Lake City, UT, USA
[b] Department of Marketing, David Eccles School of Business, University of Utah, Salt Lake City, UT, USA
[c] Medical Informatics, Intermountain Healthcare, Salt Lake City, UT, USA

ARTICLE INFO

Article history:
Received 28 January 2017
Revised 8 July 2017
Accepted 23 July 2017
Available online 25 July 2017

Keywords:
Electronic health records
Medical informatics applications
Outcome assessment

ABSTRACT

Objective: To develop and classify an inventory of near real-time outcome measures for assessing information technology (IT) interventions in health care and assess their relevance as perceived by experts in the field.

Materials and methods: To verify the robustness and coverage of a previously published inventory of measures and taxonomy, we conducted semi-structured interviews with clinical and administrative leaders from a large care delivery system to collect suggestions of outcome measures that can be calculated with data available in electronic format for near real-time monitoring of EHR implementations. We combined these measures with the most commonly reported in the literature. We then conducted two online surveys with subject-matter experts to collect their perceptions of the relevance of the measures, and identify other potentially relevant measures.

Results: With input from experienced health care leaders and informaticists, we developed an inventory of 102 outcome measures. These measures were classified into a taxonomy of commonly used measures around the categories of quality, productivity, and safety. Safety measures were rated as most relevant by subject-matter experts, especially those measuring medication processes. Clinician satisfaction and measures assessing mean time to complete tasks and time spent on electronic documentation were also rated as highly relevant.

Discussion: By expanding the coverage of our previously published inventory and taxonomy, we expect to help providers, health IT vendors and researchers to more effectively and consistently monitor the impact of EHR implementations in near real-time, and report more standardized outcomes in future studies. We identified several measures not commonly assessed by previous studies of IT implementations, especially those of safety and productivity, which deserve more attention from the broader informatics community.

Conclusion: Our inventory of measures and taxonomy will help researchers identify gaps in their measurement approaches and report more standardized measurements of IT interventions that could be shared among researchers, hopefully facilitating comparison across future studies and increasing our understanding of the impact of IT interventions in health care.

1. Background and significance

Positive outcomes associated with Electronic Health Record (EHR) systems adoption in both ambulatory and non-ambulatory settings [1–8], and financial incentives provided by the Centers for Medicare and Medicaid (CMS) Meaningful Use program, contributed to unprecedented EHR adoption in the U.S. [9]. In 2009, EHR adoption among office-based physicians was estimated to be 48% [10]; after implementation of Meaningful Use Stage 1, studies of the same population demonstrated that adoption had increased to 72% [11]. The observed changes in adoption and use of EHR systems have also contributed to an increasing number of studies assessing the impact on clinical practice of health information technology (health IT) adoption. Several studies evaluating the

* Corresponding author at: 421 Wakara Way, Suite 140, Salt Lake City, UT 84108-3514, USA.
E-mail address: tiago.colicchio@utah.edu (T.K. Colicchio).

http://dx.doi.org/10.1016/j.jbi.2017.07.014

impact of such interventions have been published in the last decades, and were discussed by a sequence of recent systematic reviews [12–15]. In one of the reviews, Buntin et al. [14] identified that studies at settings that implemented EHRs containing more functionality required by the Meaningful Use criteria, observed more positive findings as compared to those with less functionality. In another recent study commissioned by the Office of the National Coordinator for Health IT (ONC), Jones et al. [15] concluded that most studies evaluating health IT adoption projects report positive outcomes. However, despite the increasing number of positive findings, Jones et al. concluded that the results of current research are still mixed, failing to increase our understanding of the effectiveness of IT interventions in health care settings. According to their analysis, more information and evidence are necessary to understand why some organizations thrive, while others struggle when adopting health IT tools. Possible contributing factors to these gaps include insufficient information describing the implementation settings, implementation strategy and EHR capabilities, and inconsistent sets of outcome measurements [15]. In a first attempt to fill these gaps, we identified the outcome measures most commonly reported in the studies reviewed by Jones et al. and developed a taxonomy of measurements. We also identified characteristics of implementation settings and IT interventions reported in those studies [16].

In the present study, we assess if the measures identified in our previous study provide a comprehensive coverage of clinical and administrative processes by interviewing leadership from a large care delivery system implementing a commercial EHR. We identify other measures not commonly reported in the literature. We then combine the new suggested measures with those identified in our previous study, collect subject-matter experts' perceptions of the relevance of these measures, and obtain suggestions for additional measures. We also update our previously published taxonomy with the resulting measures to create an enhanced inventory. Finally, we compare the measures in our inventory to those included in reporting systems commonly required by policy makers and government agencies to assess the potential availability of data required to calculate these measures. We expect that the resulting inventory and taxonomy will help researchers select measures in future studies and identify gaps in their measurement approaches, hopefully facilitating comparison of health IT outcomes across future studies and enabling improved understanding of the impact of IT interventions in health care.

2. Materials and methods

In our previous study [16] we identified the 79 most common measures, reported in the literature, to assess the impact of health IT interventions. Since frequency of use does not necessarily assure usefulness of measure, we followed a multi-method and iterative approach to determine whether those measures provide a comprehensive coverage of clinical and administrative processes that can be impacted by the implementation of a new EHR system. The components of the method include: (1) conduct interviews with clinical and administrative leaders from a large care delivery system implementing a commercial EHR; (2) combine the newly suggested measures with those reported earlier [16] in the literature, to produce an enhanced inventory of measures; (3) collect subject-matter experts' perceptions of the relevance of the combined inventory of measures and identify additional measures suggested by these experts; (4) update our previously published taxonomy with the larger measure inventory; and (5) compare the measures in our inventory to those included in reporting systems commonly required by policy makers and government. These steps are described in detail in the subsequent sections. Fig. 1 illustrates the multi-method approach.

2.1. Step 1 – semi-structured interviews with Intermountain Healthcare leadership

We conducted semi-structured interviews with clinical and administrative leaders at Intermountain Healthcare, a not-for-profit integrated care delivery system of 22 hospitals and over 185 ambulatory care clinics covering the entire state of Utah and southern Idaho. Intermountain is conducting a large commercial EHR implementation, replacing a group of legacy systems developed and operated by Intermountain for several decades [17,18]. The aim of our interviews was to identify measures used to evaluate the impact of this transition to Intermountain's clinical and administrative processes supported by electronic data collected or impacted by their EHR systems. We first selected a convenience sample of interviewees from the Medical Informatics Department, representing eight clinical areas: Behavioral Health, Cardiovascular, Intensive Medicine, Oncology, Pediatrics, Primary Care, Surgical Services, and Women and Newborn. Given the size and complexity of the Intermountain care delivery system, we used snowball sampling [19] to obtain referrals to other potential interviewees. We asked each informant representing the clinical areas above for referrals to other personnel from the same clinical areas, or areas that work in conjunction with them. Interviews were conducted until we had interviewed at least two representatives of each clinical area and/or had no more referrals. In addition to the initial eight clinical areas, we also asked for referrals to employees from other departments such as human resources, risk management, pharmacy, implementation teams, or other departments considered relevant by the interviewees. Interviews were conducted in person or by phone according to the convenience of participants. Interviewees were asked to suggest outcome measures they consider relevant and would recommend to be tracked for monitoring the impact of the EHR implementation over time, and to classify their suggestions into the categories *quality of care*, *productivity* and *patient safety*, according to their use at Intermountain or interviewee's expertise. We considered only measures that can be calculated with data available in electronic format in order to detect the impact of the implementation in near real-time. The complete list of questions can be found in the online supplement.

2.2. Step 2 – development of a compiled inventory of outcome measures

We compared and combined the measures suggested by Intermountain interviewees with the measures reported before [16] as the most commonly used in the literature. This comparison resulted in an expanded inventory of outcome measures.

2.3. Step 3 – online surveys with subject-matter experts

Since the measures in our list include suggestions from leaders of a single care delivery system, we designed two online surveys to collect perceptions of subject-matter experts from around the country. One survey contained measures used in ambulatory settings, and the other included measures used in non-ambulatory settings. The surveys have three parts: Section 1: Respondent information (required); Section 2: Questions about the relevance of proposed outcome measures (required); and Section 3: Open-ended question for suggestions of additional measures (optional). In the questionnaire, a short description of each measure was provided. The measures were grouped by the categories *quality of care*, *productivity*, and *patient safety* according to their classification in our previous study [16] or as suggested by Intermountain interviewees. Respondents were asked to provide their perceptions about the relevance of each proposed measure when used for assessing the impact of EHR implementations in the target setting

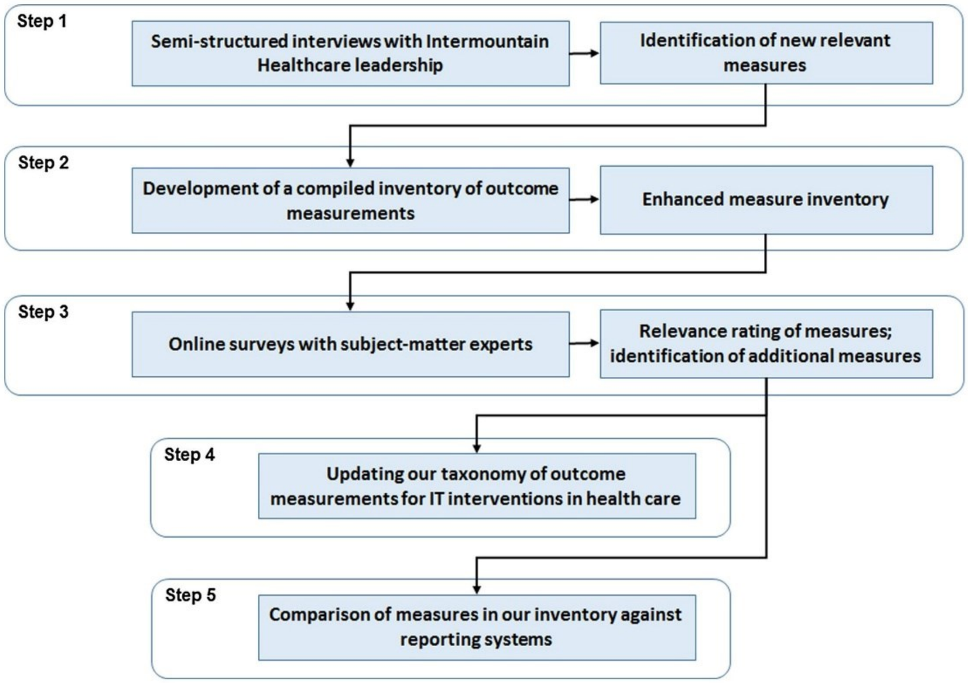

Fig. 1. Flowchart illustrating the multi-method approach.

(ambulatory vs. non-ambulatory) using a 7-point Likert scale, with options ranging from "very low relevance" (1) to "very high relevance" (7). To further clarify the concept of relevance, we provided the following example to respondents: "*The implementation of a new EHR system may introduce changes to the workflow of computerized provider order entry, therefore, it may be relevant to measure the 'volume of medical orders entered electronically' for tracking the impact of the new EHR in such a process*". Note: an option "I do not know" was provided in case interviewees were not familiar with specific outcomes. The questions of each survey can be found in the online supplement.

One of the authors (TKC) reviewed the answers to the open-ended question to identify suggestions for new measures; measures suggested by two or more respondents were selected for inclusion in our inventory. We collected survey data using REDCap electronic data capture tools hosted at Intermountain Healthcare [20]. We invited four independent researchers from the University of Utah Department of Biomedical Informatics and the Salt Lake City Veterans Affairs (VA) Medical Center to pilot the surveys. We iteratively gathered suggestions and updated the instruments before inviting the subject-matter experts to complete the surveys.

Respondents were eligible to participate if they had any prior experience conducting EHR implementations in health care settings or evaluating EHR implementations from a research standpoint. We used several methods to recruit study participants: (1) we sent invitations to the members of the American Medical Informatics Association (AMIA) Implementation Forum, and to the Healthcare Information and Management Systems Society (HIMSS) Nursing Informatics Alliance; (2) we invited authors of four systematic reviews assessing health IT adoption studies: Chaudhry et al. [12], Goldzweig et al. [13], Buntin et al. [14] and Jones et al. [15]; and (3) we invited primary faculty from several U.S. biomedical informatics programs listed on the AMIA website [21]. For the faculty invitations, we screened biographical information to identify potential participants with research interest in health IT adoption or Electronic Health Record systems, and contacted those whose contact information was available online.

Each invitee who demonstrated interest in participating was asked to indicate his/her preference of type of setting (ambulatory vs. non-ambulatory); if no preference was stated, the participant was included in the survey with fewer respondents at the time of invitation. We also asked all participants to suggest other experts to increase sample size.

2.4. Step 4 – updating our taxonomy of outcome measurements for IT interventions in health care

We have previously developed a taxonomy of outcome measurements for assessing IT interventions in health care. Our methodology was described in detail in our previous study [16]. One of the authors (TKC) first classified the new measures identified through the semi-structured interviews and online surveys into the previously published taxonomy, and identified the new taxa that had to be developed to accommodate measures not detected by our previous study [16]. As in our previous study, we used a modified Delphi process in which the first version of the classification of measures and the updated taxonomy were shared with the study co-authors, who then provided suggestions iteratively until consensus about measures' classification and nomenclature was reached.

2.5. Step 5 – comparison of measures in our inventory against reporting systems

In our previous study [16], we compared measures classified as quality of care or patient safety against performance measures included in widely used reporting systems. In the present study, we conduct the same examination for all measures in our inventory classified as quality of care or patient safety. For ambulatory settings, we used the 2016 version of the Healthcare Effectiveness Data and Information Set (HEDIS) [22]; for non-ambulatory settings, we used the CMS Hospital Compare measures data archive dated May 4, 2016 [23].

2.6. Data analysis

Each category (quality of care, productivity, patient safety) was composed of multiple individual items, each with an identical 7-point Likert scale. The items within each category were evaluated for internal consistency using Cronbach's alpha [24]. Having determined their internal consistency, the items composing each category were then combined into a composite score by taking their arithmetic average. This resulted in a composite score that remained in the 7-point scoring scheme, making the three categories comparable. Furthermore, since data were to be analyzed in a paired sample fashion, with respondents being compared to themselves across the three categories, such an approach insured that the composite scores of the three categories had a greater common underlying metric. Thus, differences of means among the three categories can be reliably interpreted as differences in relevance to the survey respondents. Two categories were compared at a time using a paired sample t-test. The reported p-values are adjusted for three multiple comparisons using Hommel's multiple comparison procedure [25]. All steps above were performed separately for ambulatory and non-ambulatory settings. Data analysis was performed using Stata version 13 statistical software [College Station, TX: StataCorp LP].

3. Results

Thirty clinical and administrative leaders from Intermountain Healthcare were interviewed (Step 1) and suggested additional measures that were combined with those extracted from our previous study [16], producing an enhanced inventory of outcome measures (Step 2). One-hundred twelve experts participated in the online surveys (Step 3), rating the relevance of the measures in our inventory and providing suggestions of additional measures. By assessing the measures suggested by interviewees and subject-matter experts, we identified seven new taxa that were added to our taxonomy (Step 4), and compared the measures in our final inventory against those required by HEDIS and Hospital Compare (Step 5).

3.1. Step 1 – semi-structured interviews with intermountain healthcare leadership

From the original sample of eight Intermountain Healthcare Informatics professionals, we collected referrals to other leaders within Intermountain's care delivery system and conducted 30 semi-structured interviews. Interviewees included leaders with an average of 16.3 years of experience with EHR systems and an average of 19.5 years of experience in their current field. They represent a wide range of clinical and administrative departments, and have mostly high-level positions at Intermountain Healthcare. Table 1 of the online supplement summarizes interviewees' characteristics.

Overall, we identified 63 outcome measures in the categories of quality of care, productivity and patient safety, measuring outcomes of ambulatory (15 measures) and non-ambulatory settings (48 measures). From the 15 measures suggested for ambulatory settings, 5 (33%) were among the most commonly reported measures in the literature [16]; from the 48 measures for non-ambulatory settings, only 7 (15%) were among the measures identified in our previous study.

3.2. Step 2 – development of a compiled inventory of outcome measures

The resulting inventory combining interviewees' suggested measures and measures from the literature contained a total of 91 measures; out of these 37 were quality of care measures (Appendices A and B), 34 were productivity measures (Appendices C and D), and 20 were safety measures (Appendices E and F).

3.3. Step 3 – online surveys with subject-matter experts

The online surveys included the 91 measures from Step 2. Surveys were open from July 7, 2016, to November 1, 2016. Forty-five experts participated in the ambulatory survey and 67 in the non-ambulatory. Since invitations were sent to membership-based lists such as the AMIA Implementation Forum and HIMSS Nursing Informatics Alliance, we were not able to identify the exact number of people who received/read the invitations; therefore, we were not able to calculate the exact response rate. Respondents of the ambulatory survey had on average 15.8 years of experience with EHR systems, and respondents of the non-ambulatory survey had 14.1 years of experience. Table 2 of the online supplement summarizes survey participants' characteristics.

3.3.1. Step 3 – internal consistency and comparison of ratings among measure categories

Internal consistency coefficients ranged from 0.86 to 0.96 for different measure categories. For the ambulatory survey, internal consistency was 0.93 for quality of care measures, 0.87 for productivity measures, and 0.86 for safety measures. For the non-ambulatory survey, internal consistency was 0.96 for quality of care measures, 0.95 for productivity measures and 0.95 for safety measures.

Safety was the most relevant category of measurements, with average scores significantly higher than quality of care in both ambulatory (safety = 5.94 vs. quality = 5.16; p = 0.001) and non-ambulatory (safety = 5.63 vs. quality = 5.17; p = 0.001) settings, and productivity in both ambulatory (safety = 5.94 vs. productivity = 4.59; p = 0.001) and non-ambulatory (safety = 5.63 vs. productivity = 4.85; p = 0.001) settings. Quality of care was the second most relevant category of measurements with higher average scores than productivity in both ambulatory (quality = 5.16 vs. productivity = 4.59; p = 0.004) and non-ambulatory (quality = 5.17 vs. productivity = 4.85; p = 0.003) settings.

3.3.2. Step 3 – relevance of quality of care measures

The ambulatory survey included 15 measures of quality of care with relevance ratings ranging from 4.24 to 5.73, and the non-ambulatory survey included 22 measures with relevance ratings ranging from 4.13 to 6.07. The measures rated as most relevant for ambulatory settings were "pneumococcal immunization documented" (mean = 5.73, SD [1.38]); followed by "breast cancer screening" (mean = 5.55, SD [1.32]); "colorectal cancer screening" (mean = 5.53, SD [1.45]); "hemoglobin A1c control" (mean = 5.40, SD [1.54]); and "diabetes bundle" (mean = 5.38, SD [1.48]). All top five relevant measures are among the most commonly reported in the literature.

The measures rated as most relevant for non-ambulatory settings were "clinician satisfaction" (mean = 6.07, SD [1.14]); followed by "venous thromboembolism (VTE) prophylaxis compliance" (mean = 5.88, SD [1.30]); "appropriate use of antibiotics" (mean = 5.88, SD [0.92]); "sepsis bundle" (mean = 5.81, SD [1.48]); and "sepsis mortality" (mean = 5.68, SD [1.71]). Three of

Table 1
Top relevant measures of quality of care.

Source	Taxa	Measure	Description	HEDIS/HC Equivalent	Relevance M (SD)	Do not know, (%)
Ambulatory – quality of care measures						
Literature	2	Pneumococcal immunization documented	Evidence of pneumococcal immunization documented in patient's electronic health records	Childhood Immunization Status Pneumococcal Vaccination Status for older adults	5.73 (1.38)	–
Literature	1	Breast cancer screening	Breast cancer screening ordered as preventive care in target patients	Breast Cancer Screening	5.55 (1.32)	–
Literature	1	Colorectal cancer screening	Colorectal cancer screening ordered as preventive care in target patients	Colorectal Cancer Screening	5.53 (1.45)	–
Literature	5	Hemoglobin A1c control	Rate of diabetes patients with hemoglobin A1c under control	Comprehensive Diabetes Care	5.40 (1.54)	–
Literature/IH	7	Diabetes Bundle	Composite measure for diabetes control	Comprehensive Diabetes Care	5.38 (1.48)	2%
Non-ambulatory – quality of care measures						
Literature	10	Clinician Satisfaction	Clinicians' satisfaction as end-user of a new or updated Health IT system	Not included	6.07 (1.14)	–
Literature/IH	3	VTE prophylaxis compliance	Rate of orders of prophylaxis for venous thromboembolism in compliance with guidelines	SCIP-VTE-2; VTE-1; VTE-2; PSI-12	5.88 (1.30)	–
Literature	3	Appropriate use of antibiotics	Orders of antibiotic drugs in compliance with guidelines	PN-6; SCIP-Inf-1; SCIP-Inf-2; SCIP-Inf-3	5.88 (0.92)	–
IH	7	Sepsis bundle	Composite measure for sepsis care measured as compliance to all composite items	Not included	5.81 (1.48)	1%
IH	4	Sepsis mortality rate	Rate of patients who died during hospitalization due to severe sepsis or septic shock	Not included	5.68 (1.71)	–

Abbreviations: IH: Intermountain Healthcare; HC: Hospital Compare.
Note: Measures are sorted by descending order of relevance.

the top 5 relevant measures are among the most commonly reported in the literature and two were suggested by Intermountain leaders. Table 1 presents the top 5 relevant quality of care measures from each survey. Appendices A and B summarize the complete list of quality of care measures.

3.3.3. Step 3 – relevance of productivity measures

The ambulatory survey included 11 productivity measures with relevance ratings ranging from 3.14 to 5.51, and the non-ambulatory survey included 23 measures with relevance ratings ranging from 3.17 to 5.92. The measures rated as most relevant for ambulatory settings were "time to provider" (mean = 5.51, SD [1.57]); followed by "patient visits" (mean = 5.04, SD [1.95]); "laboratory orders" (mean = 4.95, SD [1.82]); "net collection ratio" (mean = 4.95, SD [1.81]); and "medication orders" (mean = 4.75, SD [1.84]).

The measures rated as most relevant for non-ambulatory settings were "time spent by nurse documenting" (mean = 5.92, SD [1.47]); followed by "radiology orders" (mean = 5.40, SD [1.16]); "antibiotic turnaround time" (mean = 5.34, SD [1.29]); "ED wait time" (mean = 5.34, SD [1.61]); and "ED length of stay" (mean = 5.29, SD [1.74]). Table 2 presents the top five relevant measures from each survey. Appendices C and D summarize the complete list of productivity measures.

3.3.4. Step 3 – relevance of patient safety measures

Only two measures of patient safety were rated by the expert panel in the ambulatory survey. The two safety measures were "medication errors" (mean = 5.95, SD [1.29]) and "adverse drug events (ADEs) rate" (mean = 5.93, SD [1.35]). Both measures are among the most commonly reported in the literature.

The non-ambulatory survey included 18 measures of patient safety with relevance ratings ranging from 4.39 to 6.22. The measures rated as most relevant for non-ambulatory settings were "ADEs rate" (mean = 6.22, SD [1.11]); followed by "medication errors" (mean = 6.19, SD [1.04]); "bar-code medication

Table 2
Top relevant measures of productivity.

Source	Taxa	Measure	Description	Relevance, M (SD)	Do not Know, (%)
Ambulatory – productivity measures					
IH	18	Time to provider	Mean time between patient check-in and patient visit initiated	5.51 (1.57)	–
Literature/IH	14	Patient visits	Number of patient visits to ambulatory settings	5.04 (1.95)	–
Literature	15	Laboratory orders	Number of orders of laboratory tests	4.95 (1.82)	–
IH	16	Net collection ratio	Proportion of the amount of money received from payers in relation to the amount planned	4.95 (1.81)	4%
Literature	15	Medication orders	Number of medication orders	4.75 (1.84)	–
Non-ambulatory – productivity measures					
IH	18	Time spent by nurse documenting	Mean time spent by nurse documenting on electronic health records in the ICU	5.92 (1.47)	1%
IH	15	Radiology orders	Number of orders of imaging tests	5.40 (1.16)	–
IH	18	Antibiotic turnaround time	Mean time between antibiotic order and administration in newborn patients	5.34 (1.29)	6%
IH	18	ED wait time	Mean time between patient arrival and seen by provider in emergency departments	5.34 (1.61)	1%
Literature/IH	14	ED LOS	Length of stay of patients in emergency departments	5.29 (1.74)	–

Abbreviations: IH: Intermountain Healthcare.
Note: Measures are sorted by descending order of relevance.

Table 3
Top relevant measures of safety.

Source	Taxa	Measure	Description	HEDIS/HC Equivalent	Relevance, M (SD)	Do not know, (%)
Ambulatory – patient safety measures						
Literature	20	Medication errors	Medication errors of any source	Not included	5.95 (1.29)	–
Literature/ IH	20	ADEs rate	Rate of adverse drug events	Not included	5.93 (1.35)	–
Non-ambulatory – patient safety measures						
Literature	20	ADEs rate	Rate of adverse drug events	Not included	6.22 (1.11)	–
Literature	20	Medication errors	Medication errors of any source	Not included	6.19 (1.04)	–
IH	20	BCMA override rate	Rate of bar-coded medication administration override	Not included	6.19 (1.23)	–
Literature	20	Medication orders changed	Rate of medication orders changed following clinical decision support recommendation	Not included	6.13 (1.17)	–
IH	20	Missed home medication	Rate of medication errors caused by missing a medication during medication reconciliation	Not included	6.10 (1.10)	–

Abbreviations: IH: Intermountain Healthcare; HC: Hospital Compare.
Note: Measures are sorted by descending order of relevance.

administration (BCMA) override rate" (mean = 6.19, SD [1.23]); "medication orders changed" (mean = 6.13, SD [1.17]); and "missed home medication" (mean = 6.10, SD [1.10]). Three of the top 5 relevant measures are among the most commonly reported in the literature and two were suggested by Intermountain leaders. Table 3 presents the most relevant safety measures. Appendices E and F summarize the complete list of safety measures.

3.3.5. Step 3 – additional measures suggested by subject-matter experts

For the ambulatory survey, 25 (56%) participants answered the open-ended question. Two of the responses included general comments without suggestions of specific measures, e.g. "*I think you should be looking to measures that are much more closely linked or associated with EHR use. Many of these measures depend in large part on patient behavior, which has little to do with EHR use…*". Three participants suggested measures that require non-automated data collection methods (e.g. "*time spent by clinicians on patient care activities*"). Since our goal is to develop an inventory of measures with the ability to detect in near real-time the effect of an EHR implementation on the care delivery organization, measures that require non-automated data collection methods were not included in our inventory. We identified 24 unique outcome measures, 6 of which were suggested by 2 or more participants and were selected for inclusion in our inventory.

For the non-ambulatory survey, 35 (52%) participants answered the open-ended question. Four of the responses included general comments without suggestions of specific outcomes, e.g. "*Very comprehensive survey…*", and "*I dislike process measures. Measure the outcomes, not the process….*" Six participants suggested measures that require non-automated data collection methods, e.g. "*Clinicians' perception of verbal communication about patient post implementation*". We identified 25 unique measures, 5 of which were suggested by two or more participants and were included in our inventory. The 11 total additional measures were added to our original list, producing a final inventory of 102 outcome measures. Table 4 summarizes the additional measures included in our inventory. Table 3 of the online supplement provides the complete list of suggested measures.

Table 4
Additional measures suggested by two or more survey participants.

# Suggestions	Taxa	Measure	Description
Ambulatory measures			
9	10	Clinician Satisfaction	Clinicians' satisfaction as end-user of a new or updated Health IT system
3	18	Time to complete visits	Mean time between patient seen by provider and visit completed
3	18	Time spent by provider documenting after hours	Mean time spent by provider documenting on electronic health records after work hours
2	18	Time to sign notes	Mean time between visit completed and note signed
2	14	Patient phone calls	Number of patient phone calls during work hours
2	18	Time spent by provider documenting	Mean time spent by provider documenting on electronic health records
Non-ambulatory measures			
3	18	Time spent by provider documenting	Mean time spent by provider documenting on electronic health records
2	19	Electronic orders rate	Rate of orders entered electronically
2	20	Medication reconciliation rate	Rate of patients with medication reconciliation documented in patient electronic health records
2	18	Medication turnaround time	Mean time between medication ordered and administered
2	20	Overdue medication rate	Rate of overdue medications administered

Note: Measures are sorted by descending number of suggestions.

3.4. Step 4 – updating our taxonomy of outcome measurements for IT interventions in health care

From the 63 measures suggested by Intermountain Healthcare interviewees, we identified 6 new taxa that were added to our taxonomy: "time efficiency as a proxy for productivity" (16 measures); "hospital-acquired infection" (8 measures); "health care cost" (7 measures); "staff management" (5 measures); "appropriate use of diagnostic test" (3 measures); and "risk management" (2 measures). From the 11 additional measures suggested by the expert panel we identified an additional taxon that was added to our taxonomy: "health IT usage" (1 measure). With the added measures and taxa, the taxonomy was expanded from 15 [16] to 22 types of measurements (Fig. 2).

3.5. Step 5 – comparison of measures against reporting systems

Overall, data required for 13 (81%) measures of quality of care in ambulatory settings can be relatively easily found in the data needed to calculate HEDIS measures, including the top five relevant measures. Table 1 presents HEDIS equivalent measures for the top five relevant measures. The complete list of HEDIS equivalent measures can be found in Appendix A. HEDIS measures

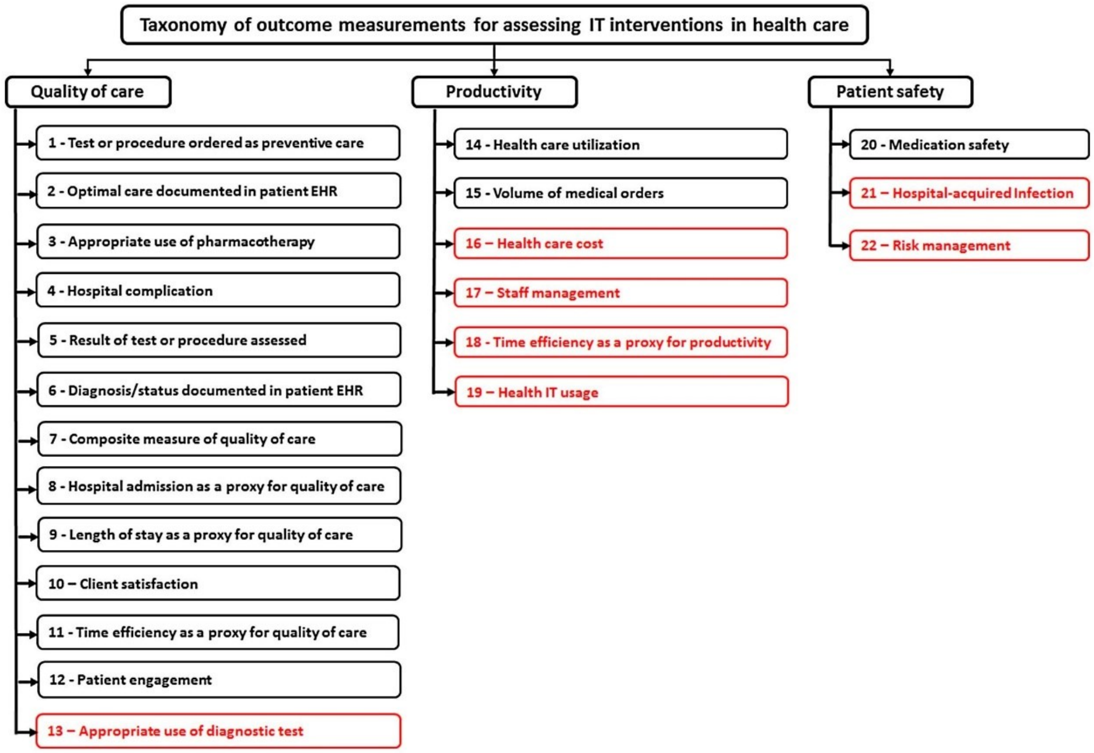

Fig. 2. Updated taxonomy of outcome measurements for assessing IT interventions in health care. Taxa in black originated from our previous study based on secondary analysis of a systematic review. Taxa in red were added from the present study based on interviews and survey responses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

do not provide data for the safety measures included in our inventory.

Data required for 6 (27%) measures of quality of care in non-ambulatory settings can be relatively easily found in the data needed to calculate the measures included in Hospital Compare. Among the top five relevant measures, only 2 have an equivalent in Hospital Compare. Table 1 presents Hospital Compare equivalent measures for the top five relevant measures. The complete list of Hospital Compare equivalent measures can be found in Appendix B. As opposed to our previous study, where none of the safety measures had an equivalent in Hospital Compare [16], 7 (35%) of the measures suggested by Intermountain leaders have an equivalent in Hospital Compare; however, none of those are among the top five relevant measures. The complete list of Hospital Compare equivalent measures can be found in Appendix F.

None of the additional measures suggested by the expert panel has an equivalent in the reporting systems consulted.

4. Discussion

Our study provides a robust inventory of outcome measures for assessing the impact of IT interventions in health care settings and a taxonomy to classify these measures. Although measures of health IT outcomes have been reported in previous research [26,27], to our knowledge, this is the first systematic inventory of measures specifically developed to assess the impact of health IT interventions through a multi-method approach that combined measures commonly reported in the literature with those suggested by experienced health care leaders and health IT adoption experts. Further, this is the first time an inventory has been rated by experts nationwide. The broader informatics community can benefit from our inventory and taxonomy in several ways. Our inventory provides a list of measures covering several relevant care processes including quality, productivity, and safety, for both ambulatory and non-ambulatory care settings. Our taxonomy will help researchers identify gaps in their measurement approaches and report more standardized measures that could facilitate comparison of health IT outcomes in future studies.

Previous studies indicate that quality of care is the most commonly used type of measurement in health IT adoption studies [15,16]. Several measures in our inventory were considered to have "moderate" or "high relevance" and were among the most commonly reported in current research, including the top five most relevant measures for ambulatory and the top three for non-ambulatory. However, we were still able to identify 14 measures suggested by Intermountain leaders and survey participants that have not been frequently used in previous literature reports, indicating that potentially relevant care processes are not being reported by researchers. In our previous study [16], we have also identified that researchers tend to use quality measures that are required by widely used reporting systems. In the present study, we confirmed this tendency for the ambulatory setting, where 81% of the measures in our list can be calculated with data provided by HEDIS and 27% of non-ambulatory measures have an equivalent in Hospital Compare.

Productivity measures received lower relevance ratings compared to quality and safety, and had the option "I don't know" more frequently selected by survey respondents. Our previous study [16] identified only 11 productivity measures commonly reported in the literature. This likely contributed to having 32 measures of productivity suggested by Intermountain leaders and survey respondents that have not been frequently used in previous research. The measures of productivity rated as most relevant often assess time efficiency processes. Six measures suggested by survey participants were measures that assess mean time to complete specific care processes or time spent on electronic documentation.

Overall, safety measures were rated as more relevant than quality and productivity, and were more frequently rated as "high relevance" or "very high relevance". Findings from our previous study [16] indicate that medication safety measures are the most commonly reported in current research, and the present study attests to their relevance, with the top eight measures rated as most relevant assessing medication safety processes. However, we identified measures of other care processes such as infectious disease management that were also considered highly relevant. Safety measures suggested by Intermountain leaders tend to be those required by reporting systems: 35% of safety measures have an equivalent in Hospital Compare; however, none of those are among the top eight relevant measures.

Although patient safety outcomes are less frequently assessed in health IT adoption studies [16], they seem to be a common concern among different stakeholders [28,29]. The subject-matter experts who answered our surveys confirmed the importance of monitoring safety outcomes by rating safety measures as the most relevant. The importance of monitoring safety processes during EHR implementations is also confirmed by several studies eliciting unintended consequences of health IT adoption, especially those introduced by computerized provider order entry (CPOE) [30], as stated in a recent study by the Food and Drug Administration (FDA) [31]. Safety concerns [30,31], usability problems [32], and EHR vendor's "legal invulnerability" [33], may also have contributed to clinician satisfaction as being rated as the most relevant measure for quality in non-ambulatory setting, and as an additional measure suggested by several respondents of the ambulatory survey. EHR impact on mean time to complete tasks and time required for documentation also seem to be common concerns among experts, and are also perceived as a common unintended adverse consequence and a barrier to health IT adoption among clinicians [34]. We did not include in our inventory suggestions of measures that require alternative, non-automated data collection methods; however, the expert panel frequently suggested outcomes that assess impact of EHR implementation on workflow, communication, and satisfaction; therefore, we recommend future research focused on alternative methods that can efficiently capture different aspects of clinician satisfaction with EHRs for continuous monitoring.

Given the complexity and high cost involved in implementing commercial EHR systems, EHRs recently adopted by care delivery systems will likely be maintained by these institutions for many years. However, similar to complex changes common in other industries [35], EHR implementations warrant ongoing monitoring, not only during the transition phase, but also to assess deployment of new versions, ongoing customization, and especially ongoing monitoring to detect failures and unintended/unexpected effects. Our proposed inventory and taxonomy can help providers, health IT vendors, and the broader informatics community to monitor such complex projects, both during the transition phase and after the system has been stabilized and ongoing monitoring and maintenance start. In addition, since target population and outcome criteria may vary across institutions, our proposed measures and taxonomy will help investigators to properly classify and report measures that assess similar outcomes with different inclusion and exclusion criteria. For example, diabetes bundles with different components could always be reported as "diabetes bundle" and classified as "composite measure of quality of care". As a result, the scientific community will be able to report more standardized measurements of health IT evaluations that can be shared among researchers, hopefully facilitating comparison among future studies, leading us to a better understating of the impact of IT interventions in health care.

4.1. Limitations

Our study has several limitations. A single author first evaluated and classified the measures suggested by interviewees and survey respondents. However, several iterations of measure classification and nomenclature were performed to minimize data misclassification. Intermountain Healthcare is a care delivery system well known for its extensive experience with informatics applications, and the perception of its leaders could differ from leaders in other organizations. We believe that the high ratings of relevance provided by the expert panel mitigate this threat to the generalizability of our findings. We were not able to calculate the exact response rate of the surveys; however, given the number of participants, and their diversity and years of experience with EHR systems, we believe that we formed a strong expert panel. Lastly, we included only HEDIS and Hospital Compare reporting systems in our analysis; nevertheless, they are widely adopted and well known to providers and researchers. The data necessary to calculate all the proposed measures may not be readily available at every care delivery system. However, data availability is likely to increase with increasing EHR adoption and the introduction of value-based reimbursement models.

5. Conclusions

We developed a robust inventory of 102 outcome measures relevant to assessing the impact of EHR implementations in health care settings according to experienced health care leaders and health IT adoption experts. We also expanded the coverage of our previously reported taxonomy that will help researchers identify gaps in their measurement approaches and report more standardized measures that could be shared among researchers in future studies. Patient safety was rated as the most relevant type of measurement for assessing the impact of EHR implementations and deserves more attention from the broader informatics community. Measures assessing clinician satisfaction, time to complete tasks and time spent on electronic documentation are also highly relevant according to the experts. We expect that our inventory of measures and taxonomy will help providers, EHR vendors, and researchers to more effectively monitor the impact of EHR implementations, and report their results with more standardized measures, hopefully facilitating comparison among future studies and leading us to a better understating of the impact of IT interventions in health care.

Acknowledgements

Authors would like to acknowledge professors Damian Borbolla, MD, MS and Charlene Weir, PhD, RN, and members of the Socio-Technical Committee at the University of Utah, Department of Biomedical Informatics for their support on the development of our surveys. We would also like to acknowledge Damian Borbolla, MD, MS, Polina Kukhareva, MS, MPH, Makoto Jones, MD, MS, and David Shields for their participation piloting the surveys, and Greg Stoddard for his contribution to the statistical analysis. We thank the leaders from Intermountain Healthcare who participated in the interviews and the respondents to our online surveys. This research was supported by Intermountain Healthcare, Salt Lake City, UT, USA. JCF has been partially supported by the National Center for Advancing Translational Sciences of the National Institutes of Health under Award Number 5UL1TR001067-03.

Conflict of interest

Authors declare that there is no conflict of interest.

Appendix A. Quality of care measures for ambulatory settings

Source	Taxa	Measure	Description	HEDIS Equivalent	Relevance M (SD)	Do not know, (%)
Ambulatory - Quality of Care Measures						
Literature	2	Pneumococcal immunization documented	Evidence of pneumococcal immunization documented in patient's electronic health records	Childhood Immunization Status Pneumococcal Vaccination Status for older adults	5.73 (1.38)	–
Literature	1	Breast cancer screening	Breast cancer screening ordered as preventive care in target patients	Breast Cancer Screening	5.55 (1.32)	–
Literature	1	Colorectal cancer screening	Colorectal cancer screening ordered as preventive care in target patients	Colorectal Cancer Screening	5.53 (1.45)	–
Literature	5	Hemoglobin A1c control	Rate of diabetes patients with hemoglobin A1c under control	Comprehensive Diabetes Care	5.40 (1.54)	–
Literature/IH	7	Diabetes Bundle	Composite measure for diabetes control	Comprehensive Diabetes Care	5.38 (1.48)	2%
IH	3	Medication Management for People with Asthma	Rate of asthma patients using appropriate medication	Medication Management for People With Asthma	5.32 (1.30)	4%
Literature	1	Osteoporosis screening	Osteoporosis screening ordered as preventive care in target patients	Comprehensive Diabetes Care	5.30 (1.31)	4%
Literature	1	Chlamydia screening	Chlamydia screening ordered as preventive care in target patients	Chlamydia Screening in Women	5.18 (1.41)	2%
IH	13	Appropriate use of DEXA scan	Rate of bone density scan ordered in compliance with guidelines	Osteoporosis Management in Women Who Had a Fracture	5.18 (1.38)	2%
Literature/IH	5	Blood pressure control	Rate of hypertensive patients with blood pressure under control	Controlling High Blood Pressure	5.04 (1.62)	–
Literature	5	LDL cholesterol control	Rate of diabetes patients with low-density lipoprotein cholesterol under control	Not Included	4.93 (1.73)	4%
IH	13	Inappropriate use of pap smear test	Pap smear test ordered not in compliance with guidelines	Not Included	4.93 (1.62)	–
IH	13	Inappropriate use of imaging tests for low back pain	Imaging test for patients with low back pain ordered not in compliance with guidelines	Use of Imaging Studies for Low Back Pain	4.86 (1.59)	4%
Literature	2	Dietary counseling documented	Evidence of dietary counseling documented in patient's electronic health records	Weight Assessment and Counseling for Nutrition and Physical Activity for Children/ Adolescents	4.71 (1.39)	–
Literature/IH	10	Patient overall experience with care provided	Patients' satisfaction with care provided	CAHPS Health Plan Survey 5.0H	4.24 (1.94)	–

Abbreviations: IH: Intermountain Healthcare.
Note: Measures are sorted by descending order of relevance.

Appendix B. Quality of care measures for non-ambulatory settings

Source	Taxa	Measure	Description	Hospital Compare Equivalent	Relevance, M (SD)	Do not now, (%)
Non-ambulatory - Quality of Care Measures						
Literature	10	Clinician Satisfaction	Clinicians' satisfaction as end-user of a new or updated Health IT system	Not included	6.07 (1.14)	–
Literature/IH	3	VTE prophylaxis compliance	Rate of orders of prophylaxis for venous thromboembolism in compliance with guidelines	SCIP-VTE-2; VTE-1; VTE-2; PSI-12	5.88 (1.30)	–
Literature	3	Appropriate use of antibiotics	Orders of antibiotic drugs in compliance with guidelines	PN-6; SCIP-Inf-1; SCIP-Inf-2; SCIP-Inf-3	5.88 (0.92)	–
IH	7	Sepsis bundle	Composite measure for sepsis care measured as compliance to all composite items	Not included	5.81 (1.48)	1%
IH	4	Sepsis mortality rate	Rate of patients who died during hospitalization due to severe sepsis or septic shock	Not included	5.68 (1.71)	–
Literature/IH	8	Readmission rate	Rate of heart failure patients readmitted within 30 days	READM-30-AMI; READM-30-CABG; READM-30-COPD; READM-30-HF; READM-30-HIP-KNEE; READM-30-HOSP_WIDE; READM-30-PN; READM-30-STK	5.60 (1.58)	1%
Literature	7	Hospital Quality Alliance Scores	Composite score of quality of care for patients with acute myocardial infarction, heart failure, pneumonia, and surgical care using CMS Hospital Compare measures	Not included	5.51 (1.42)	1%
Literature/IH	4	Pressure ulcer rate	Rate of patients who developed pressure ulcer during hospitalization	Not included	5.49 (1.64)	–
Literature	4	Venous thromboembolism rate	Rate of patients who developed venous thromboembolism during hospitalization	VTE-6; PSI-12	5.44 (1.48)	–
Literature	5	Blood glucose control	Blood glucose control in ICU inpatients	Not included	5.41 (1.42)	–
Literature/IH	4	Ventilator-associated pneumonia rate	Rate of patients with diagnosis of ventilator-associated pneumonia	Not included	5.23 (1.75)	–
Literature/IH	4	Mortality rate	Rate of patients who died during hospitalization	MORT-30-AMI; MORT-30-HF; MORT-30-PN; MORT-30-COPD; MORT-30-STK; MORT-30-CAGB	5.17 (1.67)	–
Literature/IH	10	Patient satisfaction	Rate of patients who gave their hospital a rating of 9 or 10 on a scale from 0 (lowest) to 10 (highest)	Hospital Consumer Assessment of Healthcare Providers and Systems Survey	5.04 (1.74)	1%
IH	11	Time in ventilator	Mean time of ventilator therapy	Not included	4.98 (1.64)	–
Literature	9	Hospital LOS	Length of stay of hospitalized patients	Not included	4.85 (1.61)	–
Literature	4	In-hospital bleeding rate	Rate of bleeding events during hospitalization	Not included	4.61 (1.54)	3%
IH	9	NICU LOS	Length of stay of Newborn Intensive Care Unit patients	Not included	4.60 (1.85)	9%
IH	9	Maternity LOS for unplanned c-section deliveries	Length of stay of maternity patients after unplanned c-section delivery	Not included	4.50 (1.58)	10%
IH	11	Length of unplanned c-section	Mean time of labor and delivery of unplanned c-section	Not included	4.36 (1.72)	13%

(*continued on next page*)

Appendix B. (*continued*)

Source	Taxa	Measure	Description	Hospital Compare Equivalent	Relevance, M (SD)	Do not now, (%)
IH	8	NICU admission rate	Rate of patients admitted to Newborn Intensive Care Unit	Not included	4.36 (1.88)	10%
IH	9	Maternity LOS for vaginal deliveries	Length of stay of maternity patients after vaginal delivery	Not included	4.31 (1.62)	10%
IH	11	Length of vaginal delivery	Mean time of labor and delivery of vaginal delivery	Not included	4.13 (1.63)	12%

Abbreviations: IH: Intermountain Healthcare.
Note: Measures are sorted by descending order of relevance.

Appendix C. Productivity measures for ambulatory settings

Source	Taxa	Measure	Description	Relevance, M (SD)	Do not Know, (%)
Ambulatory - Productivity Measures					
IH	18	Time to provider	Mean time between patient check-in and patient visit initiated	5.51 (1.57)	–
Literature/ IH	14	Patient visits	Number of patient visits to ambulatory settings	5.04 (1.95)	–
Literature	15	Laboratory orders	Number of orders of laboratory tests	4.95 (1.82)	–
IH	16	Net collection ratio	Proportion of the amount of money received from payers in relation to the amount planned	4.95 (1.81)	4%
Literature	15	Medication orders	Number of medication orders	4.75 (1.84)	–
Literature	15	Radiology orders	Number of orders of imaging tests	4.75 (1.96)	–
IH	14	New patients visits	Rate of new patient visits to ambulatory settings	4.57 (1.98)	–
IH	16	Net operating income	Operational income before taxes	4.46 (2.00)	9%
Literature	14	After-hours patient calls	Number of patient phone calls after work hours	4.25 (1.81)	4%
IH	17	Employee movement	Rate of employees moved permanently to a different facility or department	3.34 (1.81)	13%
IH	17	Employee turnover	Rate of employee contracts terminated	3.14 (1.69)	9%

Abbreviations: IH: Intermountain Healthcare.
Note: Measures are sorted by descending order of relevance.

Appendix D. Productivity measures for non-ambulatory settings

Source	Taxa	Measure	Description	Relevance, M (SD)	Do not know, (%)
Non-ambulatory - Productivity Measures					
IH	18	Time spent by nurse documenting	Mean time spent by nurse documenting on electronic health records in the ICU	5.92 (1.47)	1%
IH	15	Radiology orders	Number of orders of imaging tests	5.40 (1.16)	–
IH	18	Antibiotic turnaround time	Mean time between antibiotic order and administration in newborn patients	5.34 (1.29)	6%
IH	18	ED wait time	Mean time between patient arrival and seen by provider in emergency departments	5.34 (1.61)	1%
Literature/ IH	14	ED LOS	Length of stay of patients in emergency departments	5.29 (1.74)	–
IH	18	Proportion of ED door to doctor (in <30 min)	Proportion of emergency department patients seen by provider in less than 30 min	5.20 (1.55)	–
Literature	15	Medication orders	Number of orders of medications	5.19 (1.44)	–

Appendix D. (*continued*)

Source	Taxa	Measure	Description	Relevance, M (SD)	Do not know, (%)
Literature	15	Laboratory orders	Number of orders of laboratory tests	5.18 (1.40)	1%
IH	18	Time to respiratory therapy	Mean time between respiratory therapy ordered and initiation of therapy	5.16 (1.49)	3%
IH	18	Time between radiology test completed and report issued	Mean time between radiology test completed and report issued by radiologist	5.03 (1.61)	1%
IH	16	Hospital cost per ICU patient	Average total hospital cost per ICU patient	5.00 (1.65)	6%
IH	18	Time between radiology test started and completed	Mean time between radiology test started and completed	4.93 (1.63)	3%
IH	16	ICU cost per patient	Average ICU cost per patient	4.92 (1.64)	3%
IH	16	ICU cost vs. Hospital cost	Proportion of ICU cost per patient compared to hospital total cost per ICU patient	4.85 (1.67)	7%
IH	18	Time between check-in and initiation of procedure	Mean time between patient check-in and initiation of procedure in the Cath-lab	4.77 (1.88)	–
IH	18	Time between procedure finished and patient discharge	Mean time between procedure finished and patient discharge in the Cath-lab	4.56 (1.81)	–
IH	16	Variable cost per delivery case	Percentage of variation between planned cost and actual cost per delivery (maternity) case	4.54 (1.77)	9%
Literature	14	Hospitalizations	Number of patients hospitalized	4.54 (2.00)	1%
Literature	14	ED visits	Number of patient visits to emergency departments	4.53 (2.09)	–
IH	17	ICU Nurse patient ratio	Ratio of nurse per patient in the ICU	4.39 (1.80)	1%
IH	16	RVU per respiratory therapist per shift	Relative value unit of respiratory therapist per shift	4.31 (1.72)	9%
IH	17	Employee movement	Rate of employees moved permanently to a different facility or department	3.44 (1.90)	12%
IH	17	Employee turnover	Rate of employee contracts terminated	3.17 (1.75)	13%

Abbreviations: IH: Intermountain Healthcare.
Note: Measures are sorted by descending order of relevance.

Appendix E. Safety measures for ambulatory settings

Source	Taxa	Measure	Description	HEDIS Equivalent	Relevance, M (SD)	Do not know, (%)
Ambulatory - Patient Safety Measures						
Literature	20	Medication errors	Medication errors of any source	Not included	5.95 (1.29)	–
Literature/IH	20	ADEs rate	Rate of adverse drug events	Not included	5.93 (1.35)	–

Abbreviations: IH: Intermountain Healthcare.
Note: Measures are sorted by descending order of relevance.

Appendix F. Safety measures for non-ambulatory settings

Source	Taxa	Measure	Description	Hospital Compare Equivalent	Relevance, M (SD)	Do not know, (%)
Non-ambulatory - Patient Safety Measures						
Literature	20	ADEs rate	Rate of adverse drug events	Not included	6.22 (1.11)	–
Literature	20	Medication errors	Medication errors of any source	Not included	6.19 (1.04)	–
IH	20	BCMA override rate	Rate of bar-coded medication administration override	Not included	6.19 (1.23)	–
Literature	20	Medication orders changed	Rate of medication orders changed following clinical decision support recommendation	Not included	6.13 (1.17)	–
IH	20	Missed home medication	Rate of medication errors caused by missing a medication during medication reconciliation	Not included	6.10 (1.10)	–
IH	20	Drug-allergy interaction override rate	Rate of drug-allergy interaction alerts overridden during ordering process	Not included	6.05 (1.28)	–

(*continued on next page*)

Appendix F. (*continued*)

Source	Taxa	Measure	Description	Hospital Compare Equivalent	Relevance, M (SD)	Do not know, (%)
IH	20	Drug-drug interaction override rate	Rate of drug-drug interaction alerts overridden during ordering process	Not included	6.04 (1.26)	–
Literature	20	Non-recommended medications ordered	Rate of medications orders not in compliance with guidelines	Not included	5.86 (1.34)	–
IH	21	Bloodstream infection rate	Rate of hospital-acquired central line associated bloodstream infections	HAI-1; HAI-1a	5.61 (1.64)	–
IH	21	Urinary tract infection rate	Rate of hospital-acquired Foley catheter-associated urinary tract infections	HAI-2; HAI-2a	5.46 (1.76)	–
IH	21	Colon surgery infection rate	Rate of hospital-acquired surgical site infections for colon surgeries	HAI-3	5.42 (1.79)	1%
IH	21	Hospital-acquired CDiff rate	Rate of hospital-acquired infections caused by Clostridium Difficile	HAI-6	5.34 (1.76)	1%
IH	21	Hospital-acquired MRSA rate	Rate of hospital-acquired infections caused by Methicillin-resistant Staphylococcus Aureus	HAI-5	5.28 (1.64)	1%
IH	21	Hospital-acquired VRE rate	Rate of hospital-acquired infections caused by Vancomycin-resistant Enterococci	Not included	5.27 (1.63)	1%
IH	21	Hospital-acquired CRA rate	Rate of hospital-acquired infections caused by Carbapenem-resistant Acinetobacter	Not included	5.23 (1.63)	6%
IH	21	Abdominal hysterectomy infection rate	Rate of hospital-acquired surgical site infections for abdominal hysterectomy surgeries	HAI-4	5.19 (1.68)	1%
IH	22	Fall rate	Rate of patient falls during hospitalization	ASC-2	5.11 (1.88)	–
IH	22	Ventilator disconnection rate	Rate of ventilator disconnection in the ICU	Not included	4.39 (1.93)	4%

Abbreviations: IH: Intermountain Healthcare.
Note: Measures are sorted by descending order of relevance.

Appendix G. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jbi.2017.07.014.

References

[1] E.L. Ciemins, P.J. Coon, J.B. Fowles, S. Min, Beyond health information technology: critical factors necessary for effective diabetes disease management, J. Diabetes Sci. Technol. 3 (3) (2009) 452–460.

[2] J. Adler-Milstein, C. Salzberg, C. Franz, E.J. Orav, J.P. Newhouse, D.W. Bates, Effect of electronic health records on health care costs: longitudinal comparative evidence from community practices, Ann. Intern. Med. 159 (2) (2013) 97–104.

[3] U. Pöder, M. Fogelberg-Dahm, B. Wadensten, Implementation of a multi-professional standardized care plan in electronic health records for the care of stroke patients, J. Nurs. Manage. 19 (6) (2011) 810–819.

[4] J.L. Schnipper, T.K. Gandhi, J.S. Wald, R.W. Grant, E.G. Poon, L.A. Volk, et al., Effects of an online personal health record on medication accuracy and safety: a cluster-randomized trial, J. Am. Med. Inform. Assoc. 19 (5) (2012) 728–734.

[5] D.P. Connelly, Y.-T. Park, J. Du, N. Theera-Ampornpunt, B.D. Gordon, B.A. Bershow, et al., The impact of electronic health records on care of heart failure patients in the emergency room, J. Am. Med. Inform. Assoc. 19 (3) (2012) 334–340.

[6] K.M. Nazi, Veterans' voices: use of the American Customer Satisfaction Index (ACSI) Survey to identify My HealtheVet personal health record users' characteristics, needs, and preferences, J. Am. Med. Inform. Assoc. 17 (2) (2010) 203–211.

[7] P.L.T. Hoonakker, P. Carayon, R.L. Brown, R.S. Cartmill, T.B. Wetterneck, J.M. Walker, Changes in end-user satisfaction with Computerized Provider Order Entry over time among nurses and providers in intensive care units, J. Am. Med. Inform. Assoc. 20 (2) (2013) 252–259.

[8] G.W. Roberts, C.J. Farmer, P.C. Cheney, S.M. Govis, T.W. Belcher, S.A. Walsh, et al., Clinical decision support implemented with academic detailing improves prescribing of key renally cleared drugs in the hospital setting, J. Am. Med. Inform. Assoc. 17 (3) (2010) 308–312.

[9] Mathematica Policy Research, Harvard School of Public Health, Robert Wood Johnson Foundation, Health Information Technology in the United States 2013: Better Information Systems for Better Care, 2013. <www.rwjf.org/en/research-publications/find-rwjf-research/2013/07/health-information-technology-in-the-united-states-2013.html> (accessed on June 16, 2016).

[10] C.J. Hsiao, E. Hing, T.C. Socey, et al., Electronic Medical Record/Electronic Health Record Systems of Office-Based Physicians: United States, 2009 and Preliminary 2010 State Estimates, Health E-Stats, 2010 National Center for Health Statistics. <http://www.cdc.gov/nchs/data/hestat/emr_ehr_09/emr_ehr_09.htm>.

[11] D. Heisey-Grove, L.-N. Danehy, M. Consolazio, K. Lynch, F. Mostashari, A national study of challenges to electronic health record adoption and meaningful use, Med. Care 52 (2) (2014) 144–148, http://dx.doi.org/10.1097/MLR.0000000000000038.

[12] B. Chaudhry, J. Wang, S. Wu, M. Maglione, W. Mojica, E. Roth, et al., Systematic review: impact of health information technology on quality, efficiency, and costs of medical care, Ann. Intern. Med. 144 (10) (2006) 742–752.

[13] C.L. Goldzweig, A. Towfigh, M. Maglione, P.G. Shekelle, Costs and benefits of health information technology: new trends from the literature, Health Aff. 28 (2) (2009) w282–w293.

[14] M.B. Buntin, M.F. Burke, M.C. Hoaglin, D. Blumenthal, The benefits of health information technology: a review of the recent literature shows predominantly positive results, Health Aff. 30 (3) (2011) 464–471.

[15] S.S. Jones, R.S. Rudin, T. Perry, P.G. Shekelle, Health information technology: an updated systematic review with a focus on meaningful use, Ann. Intern. Med. 160 (1) (2014) 48–54.

[16] T.K. Colicchio, J.C. Facelli, G. Del Fiol, D.L. Scammon, W.A. Bowes, S.P. Narus, Health information technology adoption: understanding research protocols and outcome measurements for IT interventions in health care, J. Biomed. Inform. 63 (2016) 33–44.

[17] P.J. Haug, R.M. Gardner, K.E. Tate, R.S. Evans, T.D. East, G. Kuperman, et al., Decision support in medicine: examples from the HELP system, Comput. Biomed. Res. 27 (5) (1994) 396–418.

[18] P.D. Clayton, S.P. Narus, S.M. Huff, T.A. Pryor, P.J. Haug, et al., Building a comprehensive clinical information system from components the approach at intermountain health care, Methods Inf. Med. 42 (1) (2003) 1–7.

[19] G.R. Sadler, H.-C. Lee, R.S.-H. Lim, J. Fullerton, Research article: recruitment of hard-to-reach population subgroups via adaptations of the snowball sampling strategy: hard-to-reach populations, Nurs. Health Sci. 12 (3) (2010) 369–374.

[20] Paul A. Harris, Robert Taylor, Robert Thielke, Jonathon Payne, Nathaniel Gonzalez, Jose G. Conde, Research electronic data capture (REDCap) – a metadata-driven methodology and workflow process for providing translational research informatics support, J. Biomed. Inform. 42 (2) (2009) 377–381.

[21] AMIA Informatics Academic & Training Programs. <https://www.amia.org/education/programs-and-courses> (accessed on June 20, 2016).
[22] The National Committee for Quality Assurance HEDIS measures 2016. <https://www.ncqa.org/Portals/0/HEDISQM/HEDIS2016/HEDIS%202016%20List%20of%20Measures.pdf> (accessed on June 30, 2016).
[23] CMS Hospital Compare data archive. <https://data.medicare.gov/data/archives/hospital-compare> (accessed on July 30, 2016).
[24] J.C. Nunnally, Psychometric Theory, McGraw Hill, New York, 1967, 640 p. (University of Chicago, Chicago, IL).
[25] S.P. Wright, Adjusted p-values for simultaneous inference, Biometrics 48 (1992) 10051013.
[26] J. Adler-Milstein, G. Daniel, C. Grossmann, C. Mulvany, R. Nelson, E. Pan, et al., Return on Information: A Standard Model for Assessing Institutional Return on Electronic Health Records, Institute of Medicine, Washington, DC (Internet), 2014. Available from: <http://nam.edu/wp-content/uploads/2015/06/ReturnonInformation1.pdf> (cited 2016 Aug 17).
[27] Patient Safety Network – AHRQ, Identification and Prioritization of Health IT Patient Safety Measures. <https://psnet.ahrq.gov/resources/resource/29853> (accessed on November 1, 2016).
[28] S.R. Simon, C.A. Keohane, M. Amato, M. Coffey, B. Cadet, E. Zimlichman, et al., Lessons learned from implementation of computerized provider order entry in 5 community hospitals: a qualitative study, BMC Med. Inform. Decis. Mak. 24 (13) (2013) 67.
[29] D.W. Meeks, A. Takian, D.F. Sittig, H. Singh, N. Barber, Exploring the sociotechnical intersection of patient safety and electronic health record implementation, J. Am. Med. Inform. Assoc. 21 (e1) (2014) e28–e34.
[30] L. Cowan, Literature review and risk mitigation strategy for unintended consequences of computerized physician order entry, Nurs. Econ 31 (1) (2013) 27–31.
[31] Computerized Prescriber Order Entry Medication Safety (CPOEMS) – Uncovering and Learning from Issues and Errors. <http://www.fda.gov/downloads/Drugs/DrugSafety/MedicationErrors/UCM477419.pdf> (accessed on November 1, 2016).
[32] B. Middleton, M. Bloomrosen, M.A. Dente, B. Hashmat, R. Koppel, J.M. Overhage, et al., Enhancing patient safety and quality of care by improving the usability of electronic health record systems: recommendations from AMIA, J. Am. Med. Inform. Assoc. 20 (e1) (2013) e2–e8.
[33] R. Koppel, D. Kreda, Health care information technology vendors' "hold harmless" clause: implications for patients and clinicians, JAMA 301 (12) (2009) 1276–1278.
[34] J.S. Ash, D.F. Sittig, R. Dykstra, E. Campbell, K. Guappone, The unintended consequences of computerized provider order entry: findings from a mixed methods exploration, Int. J. Med. Inform. 78 (Suppl 1) (2009) S69–S76.
[35] A.P. Moore, R.J. Ellison, R.C. Linger, Ultra Large Scale Systems (Internet), DTIC Document, 2001. Available from: <http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA388771> (cited 2014 Sep 5).

4.8 Supplementary Materials

Table 4S.1. Interviewees' characteristics

Intermountain leadership – Semi-structured interviews	
Age, years (SD)	49.5 (10.7)
Female, n (%)	12 (40)
Role, n (%)	
Executive/VP	2 (6.7)
Director	9 (30)
Manager	9 (30)
Staff	8 (26.7)
Consultant	1 (3.3)
Other	1 (3.3)
Department, n (%)*	
Cardiovascular Care	2 (6.7)
Human Resources	3 (10)
Imaging Services	2 (6.7)
Intensive Medicine	2 (6.7)
Medical Informatics	8 (26.7)
Pharmacy	2 (6.7)
Physician Relations	1 (3.3)
Primary Care	4 (13.3)
Quality and Patient Safety	4 (13.3)
Research	1 (3.3)
Respiratory Care	2 (6.7
Women & Newborn	2 (6.7)
Current field experience, years (SD)	19.5 (11.9)
Experience with EHRs, years (SD)	16.3 (11.3)
Time working at Intermountain, years (SD)	17.4 (11.2)

Notes: * Intermountain interviewees can work for more than one department.

Table 4S.2. Survey participants' characteristics

Expert panel - Online Surveys		
	Ambulatory	**Non-ambulatory**
Age, years (SD)	50.5 (10.7)	51.5 (10.8)
Female, n (%)	27 (60)	47 (70.1)
Role, n (%)*		
Executive/VP	7 (15.6)	5 (7.5)
Director	4 (8.9)	14 (20.9)
Manager	8 (17.8)	7 (10.4)
Faculty/Researcher	15 (33.3)	18 (26.9)
Staff	6 (13.3)	15 (13.3)
Consultant	6 (13.3)	4 (13.3.)
Other	5 (11.1)	9 (11.1)
Type of company, n (%)*		
Healthcare Provider	14 (31.1)	41 (61.2)
Academic	22 (48.9)	25 (37.3)
Government	6 (13.3)	2 (3)
Health IT Vendor	2 (4.4)	4 (4.4)
Standards Organization	1 (2.2)	1 (2.2)
Other	5 (11.1)	5 (11.1)
Main educational background, n (%)		
Medicine	14 (31.1)	13 (19.4)
Nursing	17 (37.8)	35 (52.2)
Computer Science	0 (0)	5 (7.5)
Informatics	7 (15.6)	9 (13.4)
Business	2 (4.4)	2 (3)
Other	5 (11.1)	3 (4.5)
Current field experience, years (SD)	21.1 (10.4)	20.8 (12.4)
Experience with EHRs, years (SD)	15.8 (6.9)	14.1 (7.7)

Notes: * The percentile for role and type of company exceeds 100% because respondents were allowed to select more than one option for these questions.

Table 4S.3. Individual measures suggested by survey respondents

#	Setting	Measure	Description	Taxa
9	Ambulatory	Clinician satisfaction	Clinicians' satisfaction as end user of a new or updated health IT system	Client satisfaction
3	Ambulatory	Time to complete visits	Mean time between patient seen by provider and visit completed	Time efficiency as a proxy for productivity
3	Ambulatory	Time spent documenting after hours	Time spent by provider documenting on electronic health records after work hours	Time efficiency as a proxy for productivity
2	Ambulatory	Time to sign notes	Mean time between visit completed and note signed	Time efficiency as a proxy for productivity
2	Ambulatory	Patient phone calls	Number of patient phone calls during office hours	Health care utilization
2	Ambulatory	Time spent documenting	Time spent by provider documenting on electronic health records	Time efficiency as a proxy for productivity
1	Ambulatory	Adverse events rate	Rate of adverse events not involving medication	Risk management
1	Ambulatory	Appropriate use of imaging tests	Rate of imaging tests in compliance with guidelines	Appropriate use of diagnostic test
1	Ambulatory	Appropriate use of lab tests	Rate of laboratory tests in compliance with guidelines	Appropriate use of diagnostic test
1	Ambulatory	Appropriate use of medication	Rate of medication orders in compliance with guidelines	Appropriate use of pharmacotherapy
1	Ambulatory	BMI screening	Body Mass Index screening in target patients	Test of procedure ordered as preventive care
1	Ambulatory	Diagnosis codes entered	Rate of diagnosis codes entered in electronic health records	Health information technology usage
1	Ambulatory	Encounters per hour	Rate of patients seen by provider per hour	Time efficiency as a proxy for productivity
1	Ambulatory	Follow-up visit documented	Rate of patient with follow-up visit documented in patient electronic health records	Optimal care documented in patient EHR
1	Ambulatory	Influenza immunization documented	Number of patients with influenza immunization documented in patient electronic health records	Optimal care documented in patient EHR

Table 4S.3. Continued

#	Setting	Measure	Description	Taxa
1	Ambulatory	Mean time to define educational need	Mean time between patient discharged and educational need documented in patient electronic health records	Time efficiency as a proxy for quality
1	Ambulatory	Medication reconciliation rate	Rate of patients with medication reconciliation documented in patient electronic health records	Medication safety
1	Ambulatory	Patient barriers to health education documented	Patient barriers to health education documented in patient electronic health records	New
1	Ambulatory	Patient portal usage	Rate of patient portal usage	Patient engagement
1	Ambulatory	Progress notes completed	Rate of patients with progress notes completed by provider	Health IT usage
1	Ambulatory	Provider worked hours	Average number of provider (physicians or nurse practitioner) worked hours	Time efficiency as a proxy for productivity
1	Ambulatory	Rate of Medicare patients	Rate of Medicare patients seen by provider	Health care utilization
1	Ambulatory	Visit planning rate	Rate of notes reviewed before patient visit	Health information technology usage
3	Hospital	Time spent documenting	Time spent by provider documenting on electronic health records	Time efficiency as a proxy for productivity
2	Hospital	Electronic orders rate	Rate of orders entered electronically	Health IT usage
2	Hospital	Medication reconciliation rate	Rate of patients with medication reconciliation documented in patient electronic health records	Medication safety
2	Hospital	Medication turnaround time	Mean time between medication ordered and administered	Time efficiency as a proxy for productivity
2	Hospital	Overdue medication rate	Rate of overdue medications administered	Medication safety
1	Hospital	Adverse events rate	Rate of adverse events not involving medication	Risk management

Table 4S.3. Continued

#	Setting	Measure	Description	Taxa
1	Hospital	Delirium rate	Rate of delirium events in medical surgical units	Diagnosis/status documented in patient EHR
1	Hospital	Duplicate orders	Rate of duplicate orders	Medication safety
1	Hospital	Inappropriate use of lab tests	Rate of laboratory tests ordered not in compliance with guidelines	Appropriate use of diagnostic tests
1	Hospital	Inappropriate use of pathology tests	Rate of pathology tests ordered not in compliance with guidelines	Appropriate use of diagnostic tests
1	Hospital	IT staff count	Number of information technology professionals	Staff management
1	Hospital	Login time	Mean time to login into electronic health record system	Time efficiency as a proxy for productivity
1	Hospital	Mean time to administer overdue medications	Mean time between programed time for administration and actual time of administration of overdue drugs	Time efficiency as a proxy for quality
1	Hospital	Net operating income	Operational income after electronic health record systems adoption	Health care cost
1	Hospital	Overdue vital sign	Rate of patients with overdue vital sign collected	Time efficiency as a proxy for quality
1	Hospital	Pain scores	Average pain scores after pain medication administration	Result of test or procedure assessed
1	Hospital	Patient portal usage	Rate of patient portal usage	Health information technology usage
1	Hospital	Payment denial rate	Rate of payments denied by insurance companies	Health care cost
1	Hospital	Provider clicks rate	Rate of clicks during electronic health record usage by provider	Health information technology usage
1	Hospital	Readmission risk adjustment documented	Rate of patients with readmission risk adjustment documented	Diagnosis/status documented in patient EHR

Table 4S.3. Continued

#	Setting	Measure	Description	Taxa
1	Hospital	Staff burnout rate	Rate of staff burnout cases	Client satisfaction
1	Hospital	System downtime	Rate of electronic health record system downtime	Health information technology usage
1	Hospital	Time to antibiotic	Mean time between patient admission and antibiotic ordered (when needed) for newborn patients	Time efficiency as a proxy for quality
1	Hospital	Time to billing health insurance	Mean time between patient discharge and billing submission to health insurance	Time efficiency as a proxy for productivity
1	Hospital	Time to discharge	Mean time between discharge ordered and actual patient discharge	Time efficiency as a proxy for productivity

Notes: Measures are sorted by descending number of suggestions.

Table 4S.4. Ambulatory survey questions

Interview section	**Questions**
Section 1: descriptive data	What is your current role? What type of institution(s) do you currently work for? What is your main educational background (e.g. nursing, medicine, computer science)? How many years have you practiced in your current field? How many years of experience with EHR systems do you have? What is your age? Please inform your gender?
Section 2: Relevance of outcome measurements Quality of Care	1. Rate of hypertensive patients with blood pressure under control 2. Breast cancer screening ordered as preventive care in target patients 3. Chlamydia screening ordered as preventive care in target patients 4. Colorectal cancer screening ordered as preventive care in target patients 5. Composite measure for diabetes control 6. Evidence of dietary counseling documented in patient's electronic health records 7. Rate of diabetes patients with hemoglobin A1c under control 8. Rate of bone density scanning ordered in compliance with guidelines 9. Rate of imaging test for patients with low back pain ordered not in compliance with guidelines 10. Pap smear test ordered not in compliance with guidelines 11. Rate of diabetes patients with low-density lipoprotein cholesterol under control 12. Rate of asthma patients using appropriate medication 13. Osteoporosis screening ordered as preventive care in target patients 14. Patients' satisfaction with care provided 15. Evidence of pneumococcal immunization documented in patient's electronic health records

Table 4S.4. Continued

Interview section	**Questions**
Section 2: Relevance of outcome measurements Productivity	1. Number of patient phone calls after work hours 2. Rate of employees moved permanently to a different setting 3. Rate of employee contracts terminated 4. Number of orders of laboratory tests 5. Number of medication orders 6. Proportion of the amount of money received from payers in relation to the amount planned 7. Operational income before taxes 8. Rate of new patient visits to ambulatory settings 9. Number of patient visits to ambulatory settings 10. Number of orders of imaging tests 11. Mean time between patient check-in and patient visit initiated
Section 2: Relevance of outcome measurements Safety	1. Rate of adverse drug events 2. Medication errors of any source
Section 3: Open-ended comments	What measure(s) not included in our list do you consider relevant for assessing the impact of a new EHR implementation in ambulatory settings?

Table 4S.5. Nonambulatory survey questions

Interview section	**Questions**
Section 1: descriptive data	What is your current role? What type of institution(s) do you currently work for? What is your main educational background (e.g. nursing, medicine, computer science)? How many years have you practiced in your current field? How many years of experience with EHR systems do you have? What is your age? Please inform your gender?
Section 2: Relevance of outcome measurements Quality of Care	1. Orders of antibiotic drugs in compliance with guidelines 2. Blood glucose control in inpatients 3. Clinician's satisfaction as end-user of a new or updated Health IT system 4. Length of stay of hospitalized patients 5. Composite score of quality of care for patients with acute myocardial infarction, heart failure, pneumonia, and surgical care 6. Rate of bleeding events during hospitalization 7. Mean time of labor and delivery of unplanned c-section 8. Mean time of labor and delivery of vaginal delivery 9. Length of stay of maternity patients after unplanned c-section delivery 10. Length of stay of maternity patients after vaginal delivery 11. Rate of patients who died during hospitalization 12. Rate of patients admitted to Newborn Intensive Care Unit 13. Length of stay of Newborn Intensive Care Unit patients 14. Rate of patients who gave their hospital a rating of 9 or 10 on a scale from 0 (lowest) to 10 (highest) 15. Rate of patients who developed pressure ulcer during hospitalization 16. Rate of heart failure patients readmitted within 30 days 17. Composite measure for sepsis care measured as compliance to all composite items 18. Rate of patients who died during hospitalization due to severe sepsis or septic shock 19. Average time of ventilator therapy 20. Rate of patients who developed venous thromboembolism during hospitalization 21. Rate of patients with diagnosis of ventilator-associated pneumonia 22. Rate of orders of prophylaxis for venous thromboembolism in compliance with guidelines

Table 4S.5. Continued

Interview section	Questions
Section 2: Relevance of outcome measurements Productivity	1. Mean time between antibiotic order and administration in newborn patients 2. Length of stay of patients in emergency departments 3. Number of patient visits to emergency departments 4. Mean time between patient arrival and seen by provider in emergency departments 5. Rate of employees moved permanently to a different setting 6. Rate of employee contracts terminated 7. Average ICU cost per patient 8. Average total hospital cost per ICU patient 9. Proportion of ICU cost per patient compared to hospital total cost per ICU patient 10. Ratio of nurse per patient in the ICU 11. Number of patients hospitalized 12. Number of orders of laboratory tests 13. Number of orders of medications 14. Proportion of emergency department patients seen by provider in less than 30 minutes 15. Number of orders of imaging tests 16. Relative value unit of respiratory therapist per shift 17. Mean time between radiology test started and completed 18. Mean time between radiology test completed and report issued by radiologist 19. Mean time between patient check-in and initiation of procedure in the Cath-lab 20. Mean time between procedure finished and patient discharge in the Cath-lab 21. Time spent by nurses documenting on electronic health records in the ICU 22. Mean time between respiratory therapy ordered and initiation of therapy 23. Percentage of variation between planned cost and actual cost per delivery (maternity) case

Table 4S.5. Continued

Interview section	**Questions**
Section 2: Relevance of outcome measurements Safety	1. Rate of hospital-acquired surgical site infections for abdominal hysterectomy surgeries 2. Rate of adverse drug events 3. Rate of bar-coded medication administration override 4. Rate of hospital-acquired central line associated bloodstream infections 5. Rate of hospital-acquired surgical site infections for colon surgeries 6. Rate of drug-allergy interaction alerts overridden during ordering process 7. Rate of drug-drug interaction alerts overridden during ordering process 8. Rate of patient falls during hospitalization 9. Rate of hospital-acquired infections caused by Clostridium Difficile 10. Rate of hospital-acquired infections caused by Carbapenem-resistant Acinetobacter 11. Rate of hospital-acquired infections caused by Methicillin-resistant Staphylococcus Aureus 12. Rate of hospital-acquired infections caused by Vancomycin-resistant Enterococci 13. Medication errors of any source 14. Rate of medication orders changed following clinical decision support recommendation 15. Rate of medication errors caused by missing a medication during medication reconciliation 16. Rate of medications orders not in compliance with guidelines 17. Rate of hospital-acquired Foley catheter-associated urinary tract infections 18. Rate of ventilator disconnection in the ICU
Section 3: Open-ended comments	What measure(s) not included in our list do you consider relevant for assessing the impact of a new EHR implementation in hospital settings?

CHAPTER 5

DETECTING PERFORMANCE CHANGES ON QUALITY, PRODUCTIVITY, AND SAFETY OUTCOMES DURING A LARGE COMMERCIAL ELECTRONIC HEALTH RECORD SYSTEM IMPLEMENTATION

Tiago K. Colicchio, Guilherme Del Fiol, Debra L. Scammon, Watson A. Bowes III, Julio C. Facelli, Scott P. Narus *(Submitted to the Journal of the American Medical Informatics Association)*

5.1 Abstract

Objective: To detect performance changes and patterns of impact on quality, productivity, and safety outcomes during a large-scale commercial Electronic Health Record (EHR) implementation.

Materials and Methods: We conducted an interrupted time-series study with control sites. Four medium-size hospitals and 39 clinics from 5 geographic regions of a phased EHR implementation were compared against 1 medium-size and 1 large hospital and 10 clinics from 2 control regions. We monitored 41 outcomes of quality (11 measures), productivity (20 measures), and safety (10 measures) with monthly data from February 2013 to July 2017.

Results: Significant performance changes were detected after the intervention in 40

(98%) measures in at least 1 region; in 32 (78%) measures in 2 or more regions; and in 12 (29%) measures in 3 or more regions. Significant changes were detected in all quality measures in both types of settings, in all productivity measures in at least one type of setting, and in 9 safety measures in hospital settings.

Discussion: Using only data available in electronic format from two distinct EHR systems, we detected various patterns of impact and mixed time-sensitive effects with far-reaching implications for health care leaders across the country. With an increasing adoption of commercial EHR systems, it is critical for health care organizations to systematically monitor their EHR implementations.

Conclusion: Our results and methodology will guide the broader medical and informatics communities by informing *what* and *how* to continuously monitor in similar future interventions, allowing the implementation of effective responses to mitigate negative impacts.

5.2 Background and Significance

Although Electronic Health Record (EHR) systems have recently achieved widespread adoption in the U.S. [1-2], investigations of their impact have rarely focused 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 limited and 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 up to 2 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 [5].

As a first attempt to fill these gaps, we have developed and tested 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.

Implementation of a multifunctional commercial EHR system is a highly complex intervention consisting of multiple small interventions introduced in high-pressure care delivery settings. The objective of this study is to test a replicable methodology to detect performance changes and patterns of impact during a commercial EHR implementation;

we do not focus on evaluating whether clinical impacts can be attributed to the new EHR, nor do we focus on comparing legacy systems with the new EHR.

5.3 Materials and Methods

5.3.1 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; clinician documentation; problem lists; patient medical history; patient demographics; scheduling, admission, transfer and discharge; radiology information system; medication reconciliation; medication dispensing; clinical pharmacy; electronic medication administration; infectious disease management; and laboratory results.

5.3.2 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 (Figure 5.1). 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 intervention region included a 2-year baseline period before the EHR go live, followed by a 10- to 24-month intervention period, which ended when the control sites went live (July 2017). Each intervention region includes 1 hospital with 100 or more beds (except region 3, which has no hospitals fitting the inclusion criteria) and 5 to 10 primary care clinics. 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 1 medium-size hospital (243 beds), 1 large hospital (472 beds), and 10 primary care clinics. All study clinics were selected based on the primary care specialties Family Medicine, Internal Medicine, or Pediatrics. We excluded children's hospitals and specialty care clinics because they have specific populations and outcomes not easily generalizable to other settings. Figure 5.1 illustrates study design and implementation phases. Detailed characteristics of study settings can be found in Table 5S.1 in the Supplement. Intermountain Healthcare Institutional Review Board approved this study.

5.3.3 Outcome Measurements

We monitored 41 outcomes of 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 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 decided to include these measures because they are frequently used to assess clinician workload [20]. Detailed descriptions of study measures can be found in Tables 5S.2 and 5S.3 in the Supplement.

5.3.4 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 2 trend lines that represent the average change (increase/decrease) per month in the periods before and after the intervention, and produces 2 tests: (1) the immediate effect and (2) the over time effect. The immediate effect is the change in the level of the trend lines in the month after the introduction of the intervention. The immediate effect is calculated as the difference between the last predicted value generated by the model before the intervention and the first predicted value after its introduction within each region; and the difference between intervention and control groups. 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 within each region; and the difference between intervention and control groups. 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].

5.4 Results

Significant performance changes were observed following the intervention in 40 (98%) measures in at least 1 region; in 32 (78%) measures in 2 or more regions; and in 12 (29%) measures in 3 or more regions. In addition, 20 (49%) measures detected a significant difference between the 2 groups caused by a significant change that happened in the control sites; out of these, 7 (17%) detected a significant difference in 2 regions, and 13 (32%) measures detected a significant difference in 1 region.

5.4.1 Ambulatory Care Measures

The number of ambulatory care measures with a significant difference after the intervention ranged from 4 to 5 out of 12 measures per region. The most commonly significant measure was number of laboratory test orders, which significantly decreased in all intervention regions. Laboratory orders (Figure 5.2) decreased significantly immediately after the go live in four regions, ranging from 157.40 tests [95%CI (-268.33, -46.46, p=0.006] in region 4 to 796.37 tests [95%CI (-898.07, -694.68), p=0.009] in region 5, and decreased over time by 24.44 tests per month [95%CI (-41.11, -7.78), p<0.001] in region 2. Two measures detected a significant difference in four implementation regions: rate of diabetes patients with blood pressure in control (blood pressure control rate), and rate of new patient visits. Blood pressure control rate (Figure 5.3-A) decreased significantly immediately after go live in four regions, ranging from 2.55 [95%CI (-3.66, -1.43), p<0.001] in region 3 to 3.63 [95%CI (-5.17, -2.08), p<0.001] in region 4. Such decreases were followed by a steady increase over time in 3 regions, ranging from an increase of 0.40 per month [95% CI (0.27, 0.53), p<0.001] in region 4 to an increase of 1.47 per month [95% CI (1.24, 1.71), p<0.001] in region 5. The rate of new patient visits (Figure 5.3-B) decreased significantly immediately after the go live in four regions, ranging from 1.01 [95%CI (-1.59, -0.44), p=0.001] in region 1 to 2.90 [95%CI (-4.05, -1.75), p<0.001] in region 5.

Significant differences were detected in 3 measures in 3 regions: “employee movement rate,” “employee turnover rate,” and “diabetes bundle”; in 4 measures in 2 regions: “hemoglobin A1c,” “patient visits,” “radiology test orders,” and “medication for asthma”; and in 2 measures in 1 region: “time documenting in EHR,” and “time documenting in EHR after hours.” Table 5.1 lists the immediate effect for ambulatory measures and Table 5.2 lists the over time effect for ambulatory measures. Graphs of ambulatory measures can be found in Figures 5S.1 to 5S.9 in the Supplement.

5.4.2 Hospital Measures

The number of hospital measures with a significant difference after the intervention ranged from 9 to 18 out of 29 measures per region. The measures most commonly significant were emergency department (ED) length of stay (LOS), time between patient check-in and seen by provider in the ED (ED wait time), and hospital-acquired Clostridium Difficile (CDiff) rate, each detecting significant performance changes in all intervention hospitals. ED LOS (Figure 5.4) increased significantly immediately after go live in all regions, ranging from 0.18 hours [95%CI (0.02, 0.33), p=0.02] in region 1 to 0.53 hours [95%CI (0.47, 0.59), p<0.001] in region 2. Such increases were followed by a significant decrease over time in 3 regions, ranging from 0.02 hours per month [95%CI (-0.02, -0.01), p<0.001] in region 2 to 0.08 hours per month [95%CI (-0.10, -0.06), p<0.001] in region 5. ED wait time (Figure 5.5) increased significantly immediately after the go live in 3 regions, ranging from 8.44 minutes [95%CI (4.87, 12.00), p<0.001] in region 5 to 9.37 minutes [95%CI (5.95, 12.78), p<0.001] in region 2. A significant decrease over time in ED wait time was detected in all regions, ranging from 0.27 minutes per month [95%CI (-0.49, -0.06), p=0.01] in region 1 to 1.33 minutes per month [95%CI (-1.72, -0.94), p<0.001] in region 5. CDiff infection rate (Figure 5.6) decreased significantly immediately after the go live in region 1 by 7.11 [95%CI (-14.37, 0.13), p=0.05] and in region 2 by 6.07 [95%CI (-8.32, -3.82), p<0.001]. In the post-intervention period, infection rate continued to decrease over time in region 2 by 0.22 per month [95%CI (-0.40, -0.04), p=0.01], and decreased in region 4 by 0.39 per month [95%CI (-0.60, -0.18), p<0.001], whereas in region 5 it increased by 0.87 per month [95%CI (0.65, 1.69), p=0.04].

Significant differences were detected in 6 measures in 3 regions: “ED visits,” “employee turnover rate,” “newborn intensive care unit (NICU) admissions,” “NICU LOS,” “laboratory test orders,” and “time to complete radiology tests.” Significant differences were detected in 13 measures in 2 regions: “abdominal hysterectomy infection rate,” “bloodstream infection rate,” “colon surgery infection rate,” “electronic orders rate,” “employee movement rate,” “falls rate,” “Methicillin-resistant

Staphylococcus aureus (MRSA) infection rate," "hospitalizations," "mortality rate," "patient satisfaction rate," "pressure ulcer rate," "radiology orders," and "time to sign radiology tests." A significant difference was detected in 6 measures in 1 region: "adverse drug events (ADEs) rate," "hospital LOS," "Carbapenem-resistant Acinetobacter (CRA) infection rate," "Vancomycin-resistant Enterococci (VRE) infection rate," "readmission rate," and "time documenting in EHR." Table 5.3 lists the immediate effect for hospital measures and Table 5.4 lists the over time effect for hospital measures. Graphs of hospital measures can be found in Figures 5S.10 to 5S.35 in the Supplement.

5.5 Discussion

To the best of our knowledge, this is the largest evaluation of a commercial EHR implementation, both in terms of the number and variety of settings, measures, and data points. Using only data available in electronic format from two distinct EHR systems, we detected 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. Such changes may affect care outcomes over time for several months, and the same outcomes may be similarly affected across geographically dispersed settings. Our results and methodology will guide the broader medical and informatics communities by informing what and how to continuously monitor in similar future implementations.

We detected seasonal effects that were maintained in control sites, but were disrupted in intervention sites. ED length of stay and wait time increased significantly immediately after go live with a steady recovery in most intervention regions, whereas most control sites sustained seasonal patterns in the postintervention period. ED visits changed less uniformly and may not have affected the LOS outcomes; however, LOS may directly affect wait time, since longer stays may hamper providers' capacity to admit more patients, leading to longer wait times. The prevalence of these effects across regions lends support for implementation of strategies to improve clinician efficiency in time-constrained departments such as the ED. These strategies must be implemented for at least 1 year after go live, as demonstrated by our findings. Blood pressure control in diabetic patients tends to decrease in the winter [24]; such a pattern was observed in region 5, which went live in the Fall of 2016, with blood pressure control decreasing immediately after go live in both intervention and control groups. Such seasonal effects must be considered when choosing the most appropriate go live time. Laboratory and radiology orders frequently decreased immediately after go live across ambulatory regions. Total patient visits decreased significantly immediately after go live in regions 4 and 5 potentially affecting the number of orders. Another alternative explanation is a decrease in inappropriate orders due to the implementation of system-wide order sets, as reported in previous studies [25-26]. Employee turnover increased significantly in 2 ambulatory and 2 hospital regions, which may suggest an effect of an increasing EHR-associated physician burnout [6-7]; however, such a hypothesis needs to be further explored. An improvement was observed in time to complete radiology tests, which decreased significantly both immediately after go live and over time in 3 regions.

Changes in other important outcomes such as ADEs and mortality rate were less frequently significant and may have been affected by other factors not assessed by this study.

Time spent by provider documenting in EHR after the intervention frequently showed a downward slope, which is consistent with a more intense impact in the first moths after go live, as demonstrated by other outcomes. The lack of baseline data is a barrier to the interpretation of this trend; therefore, we recommend future research exploring electronic documentation using a longitudinal design with baseline performance to allow more complete assessments.

Significant changes were less frequently observed in safety measures, with the exception of CDiff infections, which consistently improved across 3 intervention hospitals, including a decrease both immediately after go live and over time in region 2.

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 [27]. In health care, similar reporting is required by policy makers [28] and the government [29], although with an underlying focus on payment and provider benchmarking, and most often done retrospectively. As demonstrated by Smith and Koppel[30], the intersection between patients, clinicians, and health IT has several misalignments that emerge from complex interactions happening in high-pressure care delivery settings; in such a complex environment, implementation of a new EHR will inevitably add to the complexity of the several aspects of care with which the EHR interacts[31]. Our study findings suggest that EHR implementation warrants an ongoing, near real-time, and systematic monitoring, similar to approaches adopted in the aviation industry. Monitoring should be present not only during the transition phase, but also continuously in order to detect changes caused by new versions, implementation of new modules, subtle changes introduced through configuration (e.g., CDS alerts, order sets), system malfunction, and human adaptation. Our findings also indicate that no single measure is sufficient for tracking such diverse impacts, which highlights the importance of using a large and diverse set of measures [17]. The measures can be tracked on a monthly basis or even near real-time depending on data availability. With an almost ubiquitous adoption of commercial EHR systems [1-2], with many large integrated networks and academic medical centers adopting commercial EHRs [32-34], it is critical for health care organizations to systematically monitor their EHR implementations. Such an approach will help to: (1) increase detection of significant deviations from baseline performance; (2) allow for implementation of strategies to early detect and mitigate negative effects; and (3) continuously increase our understanding of the full impact of health IT interventions on quality, productivity, and safety outcomes.

5.5.1 Limitations

Although our methodology effectively detected various performance changes, it does not explain how and why changes happened. To mitigate this limitation, we are currently conducting a complementary qualitative analysis to identify both sociotechnical changes introduced by the new EHR implementation that could help explain the effects detected in the present study, and potential confounders to add to our model. Intervention and control groups are located in different geographical areas and have different patient volumes; we mitigated this limitation by making comparisons within each group before comparing between groups. 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. The commercial EHR implemented at Intermountain 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.

5.6 Conclusion

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. We detected various patterns of impact and mixed time-sensitive effects. Significant performance changes were observed following the intervention in 40 (98%) measures in at least 1 region; in 32 (78%) measures in 2 or more regions; and in 12 (29%) measures in 3 or more regions. 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 to detect unexpected effects earlier and more precisely, allowing the implementation of effective responses to mitigate negative impacts.

5.6.1 Acknowledgements

We thank the teams from Intermountain Healthcare Enterprise Data Warehouse, Data Analytics, and multidisciplinary Clinical Programs who contributed to the collection and interpretation of data necessary to calculate several measures used in this study. Greg Stoddard, MS, University of Utah, Salt Lake City, assisted with statistical analysis for the study outcomes. This research was supported by Intermountain Healthcare, Salt Lake City, UT, USA. JCF has been partially supported by the National Center for Advancing Translational Sciences of the National Institutes of Health under Award Number 5UL1TR001067-03.

5.7 References

[1] Adoption of electronic health record systems among U.S. non-federal acute care hospitals: 2008-2015 [Internet]. [cited 2017 August 10]. Available from: https://dashboard.healthit.gov/evaluations/data-briefs/non-federal-acute-care-hospital-ehr-adoption-2008-2015.php

[2] Office-based physician electronic health record adoption [Internet]. [cited 2017 August 10]. Available from: https://dashboard.healthit.gov/quickstats/pages/physician-ehr-adoption-trends.php

[3] Kellermann AL, Jones SS. What it will take to achieve the as-yet-unfulfilled promises of health information technology. Health Aff. 2013 Jan 1;32(1):63–8.

[4] Buntin MB, Burke MF, Hoaglin MC, Blumenthal D. The benefits of health information technology: a review of the recent literature shows predominantly

positive results. Health Aff. 2011 Mar 1;30(3):464–71.

[5] Jones SS, Rudin RS, Perry T, Shekelle PG. Health information technology: an updated systematic review with a focus on meaningful use. Ann Intern Med. 2014 Jan 7;160(1):48–54.

[6] Meigs SL, Solomon M. Electronic health record use a bitter pill for many physicians. Perspect Health Inf Manag. 2016;13:1d.

[7] Shanafelt TD, Dyrbye LN, West CP. Addressing physician burnout: the way forward. JAMA. 2017 Mar 7;317(9):901–2.

[8] Robert S. Rudin P, Spencer S. Jones P, Paul Shekelle MD, Richard J. Hillestad P, and Emmett B. Keeler P. The value of health information technology: filling the knowledge gap. Am J Manag Care. 2014 Nov;20(11 Spec No. 17):eSP1-8.

[9] Colicchio TK, Facelli JC, Del Fiol G, Scammon DL, Bowes III WA, Narus SP. Health information technology adoption: understanding research protocols and outcome measurements for IT interventions in health care. J Biomed Inform. 2016 Oct;63:33–44.

[10] Sittig DF, Singh H. A new sociotechnical model for studying health information technology in complex adaptive healthcare systems. Qual Saf Health Care. 2010 Oct 1;19(Suppl 3):i68–74.

[11] Vishwanath A, Singh SR, Winkelstein P. The impact of electronic medical record systems on outpatient workflows: A longitudinal evaluation of its workflow effects. Int J Med Inform. 2010 Nov;79(11):778–91.

[12] McCormick D, Bor DH, Woolhandler S, Himmelstein DU. Giving office-based physicians electronic access to patients' prior imaging and lab results did not deter ordering of tests. Health Aff (Millwood). 2012;31(3):488-96.

[13] Herrin J, da Graca B, Nicewander D, Fullerton C, Aponte P, Stanek G, et al. The effectiveness of implementing an electronic health record on diabetes care and outcomes. Health Serv Res. 2012;47(4):1522-40.

[14] Davis AM, Cannon M, Ables AZ, Bendyk H. Using the electronic medical record to improve asthma severity documentation and treatment among family medicine residents. Fam Med. 2010;42(5):334-7.

[15] Bennett KJ, Steen C. Electronic medical record customization and the impact upon chart completion rates. Fam Med. 2010 May;42(5):338–42.

[16] Colicchio TK, Del Fiol G, Stoddard JG, Narus SP. Evaluation of a systematic methodology to detect in near real-time performance changes during electronic

health record system implementations: a longitudinal study. AMIA Annu Symp Proc. 2017 (Accepted).

[17] Colicchio TK, Fiol GD, Scammon DL, Bowes III WA, Facelli JC, Narus SP. Development and classification of a robust inventory of near real-time outcome measurements for assessing information technology interventions in health care. J Biomed Inform. 2017 Sep;73:62–75.

[18] G.J. Kuperman, R.M. Gardner, T.A. Pryor. HELP: A dynamic hospital information system. Springer, New York. 1991.

[19] Clayton PD, Narus SP, Huff SM, Pryor TA, Haug PJ, et al. Building a comprehensive clinical information system from components: the approach at Intermountain Health Care. Methods Inf Med. 2003;42(1):1–7.

[20] Arndt BG, Beasley JW, Watkinson MD, Temte JL, Tuan W-J, Sinsky CA, et al. Tethered to the EHR: primary care physician workload assessment using EHR event log data and time-motion observations. Ann Fam Med. 2017 Sep 1;15(5):419–26.

[21] Linden A. Conducting interrupted time-series analysis for single- and multiple-group comparisons. Stata J 2015;15(2):480-500.

[22] Newey WK, West KD. A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica 1987;55:703–708.

[23] Cumby RE, Huizinga J. (1992). Testing the autocorrelation structure of disturbances in ordinary least squares and instrumental variables regressions. Econometrica 1992;60:185–195.

[24] Hermann JM, Rosenbauer J, Dost A, Steigleder-Schweiger C, Kiess W, Schöfl C, et al. Seasonal variation in blood pressure in 162,135 patients with type 1 or type 2 Diabetes Mellitus. J Clin Hypertens. 2016 Apr 1;18(4):270–8.

[25] Romano MJ, Stafford RS. Electronic health records and clinical decision support systems: impact on national ambulatory care quality. Arch Intern Med. 2011 May 23;171(10):897–903.

[26] Ansari F, Gray K, Nathwani D, Phillips G, Ogston S, Ramsay C, et al. Outcomes of an intervention to improve hospital antibiotic prescribing: interrupted time series with segmented regression analysis. J Antimicrob Chemother. 2003 Nov 1;52(5):842–8.

[27] Di Gravio G, Mancini M, Patriarca R, Costantino F. Overall safety performance of the air traffic management system: indicators and analysis. Journal of Air Transport Management. 2015 May 1;44:65–9.

[28] The national committee for quality assurance HEDIS measures 2016. Accessed at https://www.ncqa.org/Portals/0/HEDISQM/HEDIS2016/HEDIS%202016%20List%20of%20Measures.pdf on August 10, 2017.

[29] CMS Hospital Compare data archive. Accessed at https://data.medicare.gov/data/archives/hospital-compare on August 10, 2017.

[30] Smith SW, Koppel R. Healthcare information technology's relativity problems: a typology of how patients' physical reality, clinicians' mental models, and healthcare information technology differ. J Am Med Inform Assoc. 2014 Feb;21(1):117–31.

[31] Wiedemann LA. A look at unintended consequences of EHRs. Health Manag Technol. 2012 Feb;33(2):24–5.

[32] Mayo Clinic launches nationwide Epic EHR implementation at 1st Wisconsin sites [Internet]. [cited 2017 Aug 30]. Available from: http://www.beckershospitalreview.com/healthcare-information-technology/mayo-clinic-launches-nationwide-epic-ehr-implementation-at-1st-wisconsin-sites.html

[33] Vanderbilt is a case study for the dreaded EHR conversion [Internet]. Modern Healthcare. [cited 2017 May 4]. Available from: http://www.modernhealthcare.com/article/20170501/NEWS/170509989

[34] VA Secretary announces decision on next-generation electronic health record [Internet]. [cited 2017 Aug 30]. Available from: https://www.va.gov/opa/pressrel/pressrelease.cfm?id=2914

Table 5.1 Immediate effect for ambulatory care measures.

Measure	Region 1 vs. Control (95% CI)	p Value	Region 2 vs. Control (95% CI)	p Value	Region 3 vs. Control (95% CI)	p Value	Region 4 vs. Control (95% CI)	p Value	Region 5 vs. Control (95% CI)	p Value
Blood pressure	-	-	-3.33 (-5.82, -0.85)	0.01	-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 compliance rate	-	-	-2.89 (-6.18, 0.39)	0.08	-4.28 (-7.48, -1.08)	0.01	-1.44 (-4.39, 1.50)	0.33	-8.53 (-12.37, -4.70)	<0.001
Hemoglobin A1c control rate	-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)	0.01a	-0.01 (-1.97, 1.94)	0.98
Controller relieve usage rate	-26.04 (-38.86, -13.21)	<0.001a	-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
Employee movement	-0.67 (-1.41, 0.06)	0.07	0.69 (0.14, 1.25)	0.01a	-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	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)	0.01
Number of laboratory test orders	-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)	0.01	-796.37 (-898.07, -694.68)	<0.001
New patient visits rate	-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)	<0.001a	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	-61.29 (-102.75, -19.83)	0.004	-27.46 (-51.54, -3.38)	0.02	13.86 (4.81, 22.92)	0.003a	-	-	-1.92 (-18.62, 14.78)	0.81

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

Table 5.2 Over time effect for ambulatory care measures.

Measure	Region 1 vs. Control (95% CI)	p Value	Region 2 vs. Control (95% CI)	p Value	Region 3 vs. Control (95% CI)	p Value	Region 4 vs. Control (95% CI)	p Value	Region 5 vs. Control (95% CI)	p Value
Blood pressure	-	-	0.40 (0.24, 0.55)	<0.001[a]	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	-	-	0.45 (0.21, 0.69)	<0.001[a]	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 rate	-0.15 (-0.26, -0.03)	0.01	0.22 (0.11, 0.32)	<0.001[a]	0.13 (-0.11, 0.39)	0.28	-0.07 (-0.36, 0.20)	0.58	-1.11 (-1.32, -0.89)	<0.001
Controller relieve usage rate	-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
Employee movement	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[a]	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
Number of laboratory test orders	2.84 (-3.57, 9.27)	0.38	-24.44 (-41.11, -7.78)	0.01	33.12 (26.24, 39.99)	<0.001[a]	2.89 (-10.83, 16.63)	0.67	54.84 (37.45, 72.23)	<0.001[a]
New patient visits rate	-0.18 (-0.02, -0.10)	0.001	-0.01 (-0.05, 0.04)	0.82	0.01 (-0.15, 0.17)	0.9	-0.02 (-0.11, 0.05)	0.51	0.10 (0.01, 0.20)	0.03[a]
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	3.45 (0.70, 6.19)	0.01[a]	-1.84 (-3.99, 0.29)	0.09	1.20 (0.37, 2.02)	0.005[a]	-	-	-1.75 (-4.61, 1.10)	0.22
Time in EHR	-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 in EHR after hours	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

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

Table 5.3 Immediate effect for hospital measures

Measure	Region 1 vs. Control (95% CI)	p Value	Region 2 vs. Control (95% CI)	p Value	Region 4 vs. Control (95% CI)	p Value	Region 5 vs. Control (95% CI)	p Value
Hospital LOS (in days)	-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[a]	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 (in days)	-1.30 (-2.53, -0.07)	0.04	0.14 (-1.36, 1.66)	0.84	-0.86 (-2.91, 1.17)	0.4	-2.35 (-5.59, 0.88)	0.15
Patient satisfaction	-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[a]	-7.11 (-13.80, -0.42)	0.04	-0.53 (-12.41, 11.34)	0.98
ED LOS	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[a]
ED wait time minutes)	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
Employee movement	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	-0.11 (-0.32, 0.08)	0.26	0.27 (0.06, 0.47)	0.01[a]	0.33 (0.08, 0.59)	0.009	0.33 (0.05, 0.62)	0.01
Hospitalizations	2.89 (-42.77, 48.55)	0.9	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 orders	-1820.99 (-3396.21, -245.76)	0.02	15460.20 (10313.50, 20606.89)	<0.001[a]	704.64 (-5328.30, 6737.58)	0.81	5066.42 (1440.93, 8691.91)	0.007

Table 5.3 Continued

Measure	Region 1 vs. Control (95% CI)	p Value	Region 2 vs. Control (95% CI)	p Value	Region 4 vs. Control (95% CI)	p Value	Region 5 vs. Control (95% CI)	p Value
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	-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	-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
Abdominal hysterectomy infection	4.16 (-0.35, 8.69)	0.07	0.80 (-0.45, 2.06)	0.2	-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[a]	-0.25 (-2.87, 2.36)	0.84
Bloodstream infection	-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	3.68 (-4.80, 12.17)	0.39	-2.32 (-14.44, 9.79)	0.7	-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	-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	-	-	1.47 (0.92, 2.01)	<0.001	-0.13 (-1.08, 0.81)	0.77	-0.16 (-0.66, 0.33)	0.5
Hospital-acquired MRSA infection	-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	-6.80 (-9.59, -4.01)	<0.001[a]	-1.23 (-3.87, 1.39)	0.35	-0.21 (-1.03, 0.60)	0.6	1.56 (1.05, 2.06)	<0.001
Urinary tract infection	-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)	0.2

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

Table 5.4 Over time effect for hospital measures

Measure	Region 1 vs. Control (95% CI)	p Value	Region 2 vs. Control (95% CI)	p Value	Region 4 vs. Control (95% CI)	p Value	Region 5 vs. Control (95% CI)	p Value
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	0.24 (0.08, 0.40)	0.004	-0.05 (-0.22, 0.12)	0.55	0.10 (-0.14, 0.35)	0.4	0.37 (0.07, 0.67)	0.01
Pressure ulcer rate	-0.01 (-0.02, 0.01)	0.7	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
ED LOS	-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	-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
Employee movement	-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	-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[a]	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	-0.03 (-0.11, 0.04)	0.4	-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 orders	-134.36 (-300.87, 32.15)	0.11	-666.84 (-1134.87, -198.82)	0.006[a]	-2275.74 (-2924.54, -1626.94)	<0.001[a]	-4255.47 (-4706.84, -3804.11)	<0.001

Table 5.4 Continued

Measure	Region 1 vs. Control (95% CI)	p Value	Region 2 vs. Control (95% CI)	p Value	Region 4 vs. Control (95% CI)	p Value	Region 5 vs. Control (95% CI)	p Value
Radiology test orders	18.11 (1.05, 35.17)	0.03[a]	67.71 (39.64,	<0.001	28.38 (-14.48, 71.24)	0.19	-96.93 (-149.56, -	<0.001
Time in EHR	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	-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	0.02 (-0.01, 0.05)	0.07	0.06 (0.05, 0.08)	<0.001	0.04 (0.02, 0.06)	<0.001	0.12 (0.10, 0.15)	<0.001
Abdominal hysterectomy infection	0.42 (0.01, 0.83)	0.04	-0.13 (-0.27, -0.01)	0.04[a]	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	0.03 (-0.15, 0.22)	0.7	0.09 (0.05, 0.12)	<0.001	0.05 (0.02, 0.06)	<0.001	-0.01 (-0.06, 0.04)	<0.001
Colon surgery infection	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	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	-	-	-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	-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	-0.64 (-0.94, -0.35)	<0.001	0.03 (-0.22, 0.29)	0.79	0.19 (0.12, 0.26)	<0.001[a]	0.06 (0.02, 0.10)	0.004
Urinary tract infection	-0.06 (-0.25, 0.11)	0.47	-0.11 (-0.19, -0.04)	0.003[a]	-0.07 (-0.21, 0.08)	0.34	0.07 (-0.32, 0.46)	0.72

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

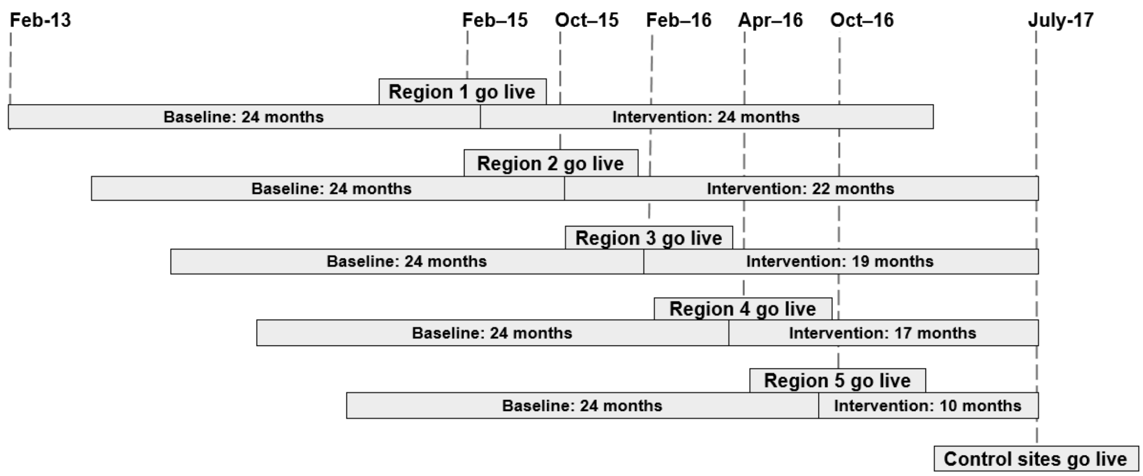

Figure 5.1 Illustration of study design and EHR go live in the first five regions.

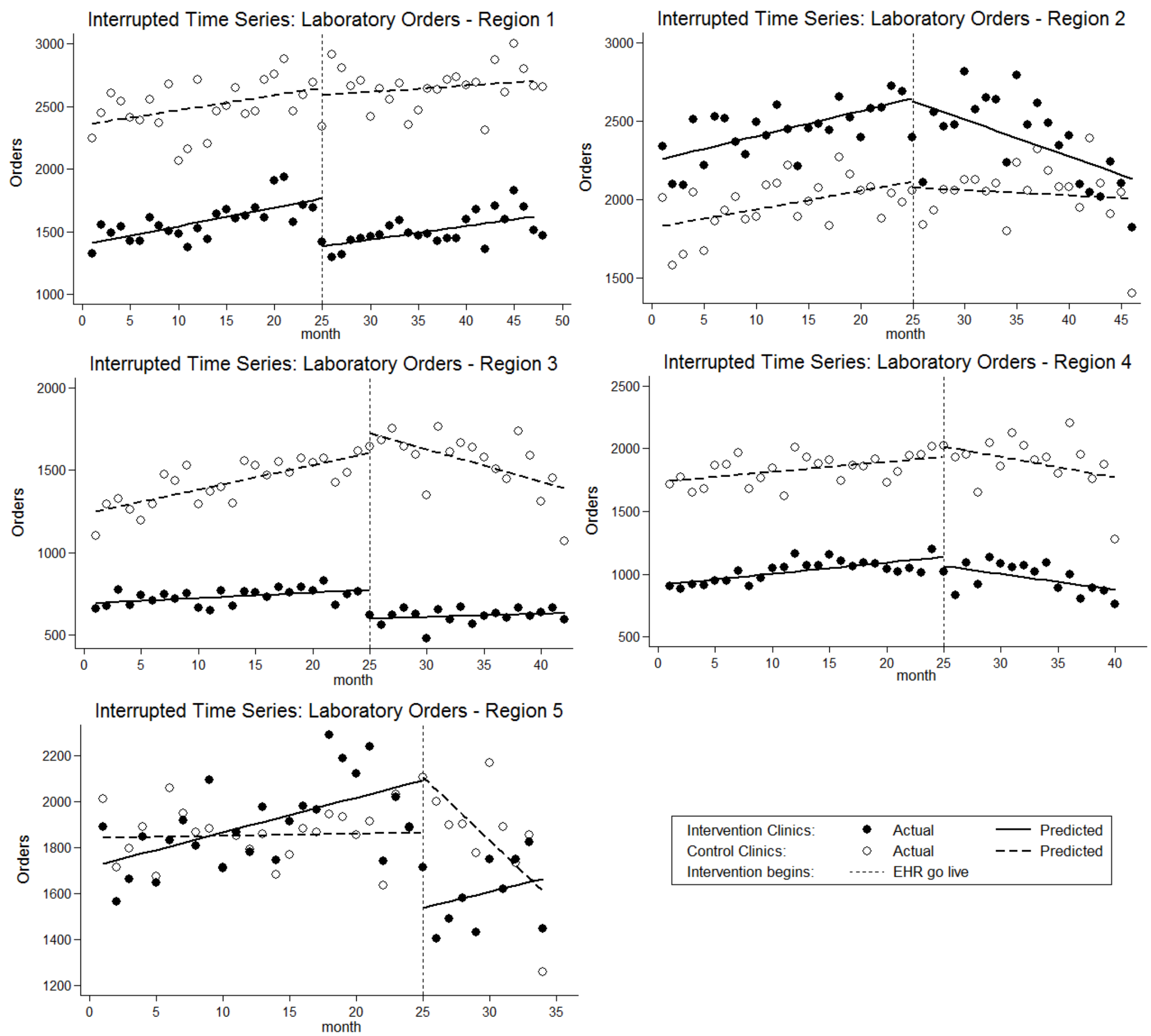

Figure 5.2 Number of outpatient laboratory orders in five regions.

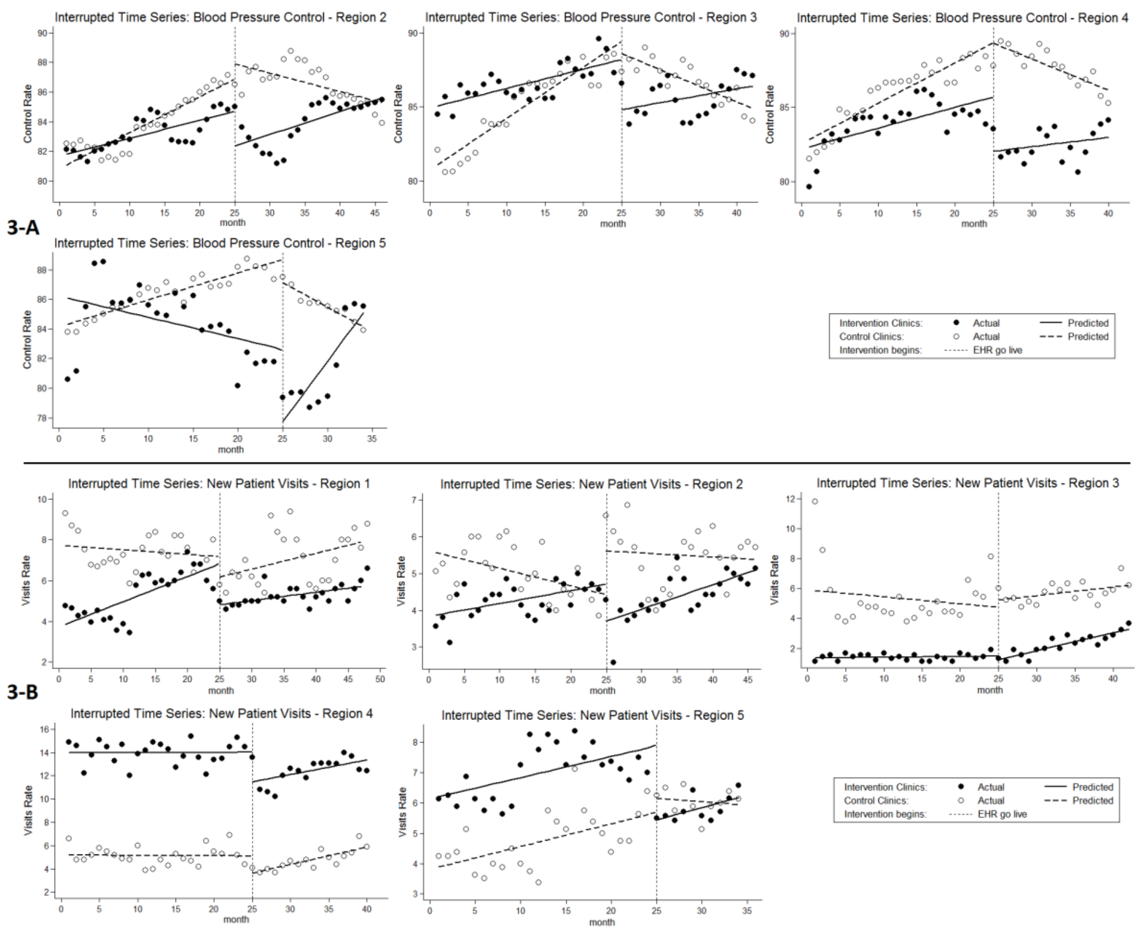

Figure 5.3 Rate of diabetic patients with blood pressure in control in regions 2, 3, 4, and 5 and rate of new patient visits in all regions.

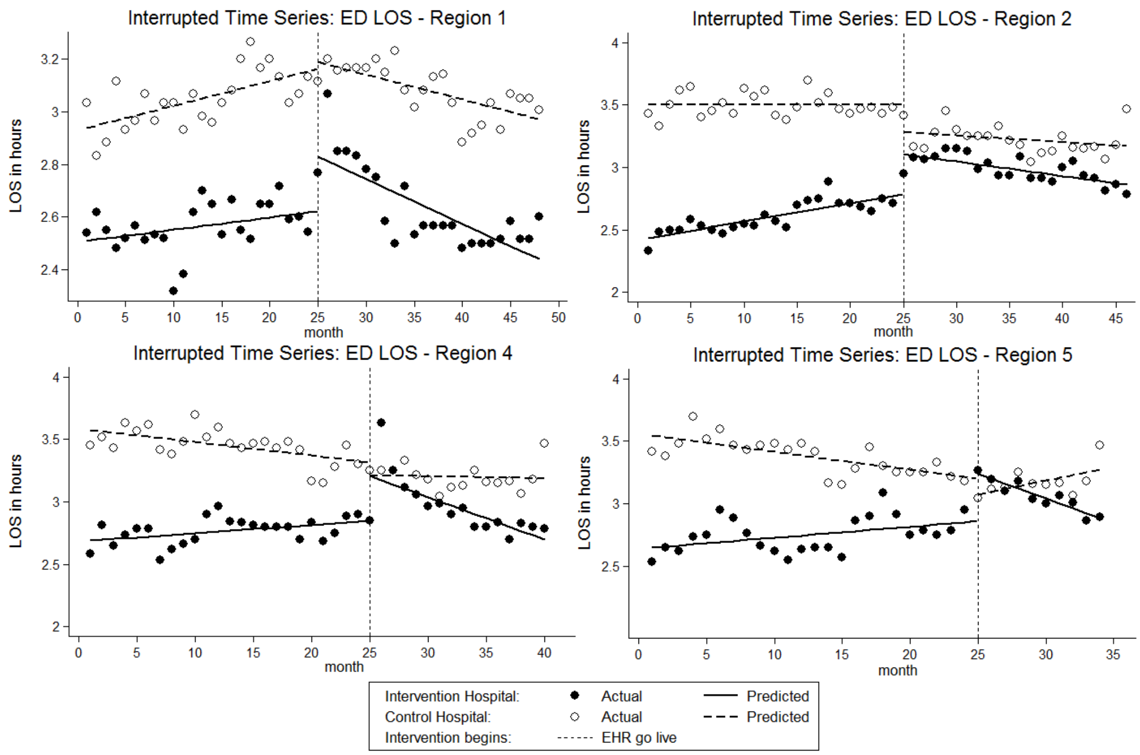

Figure 5.4 Emergency department length of stay in all hospital regions.

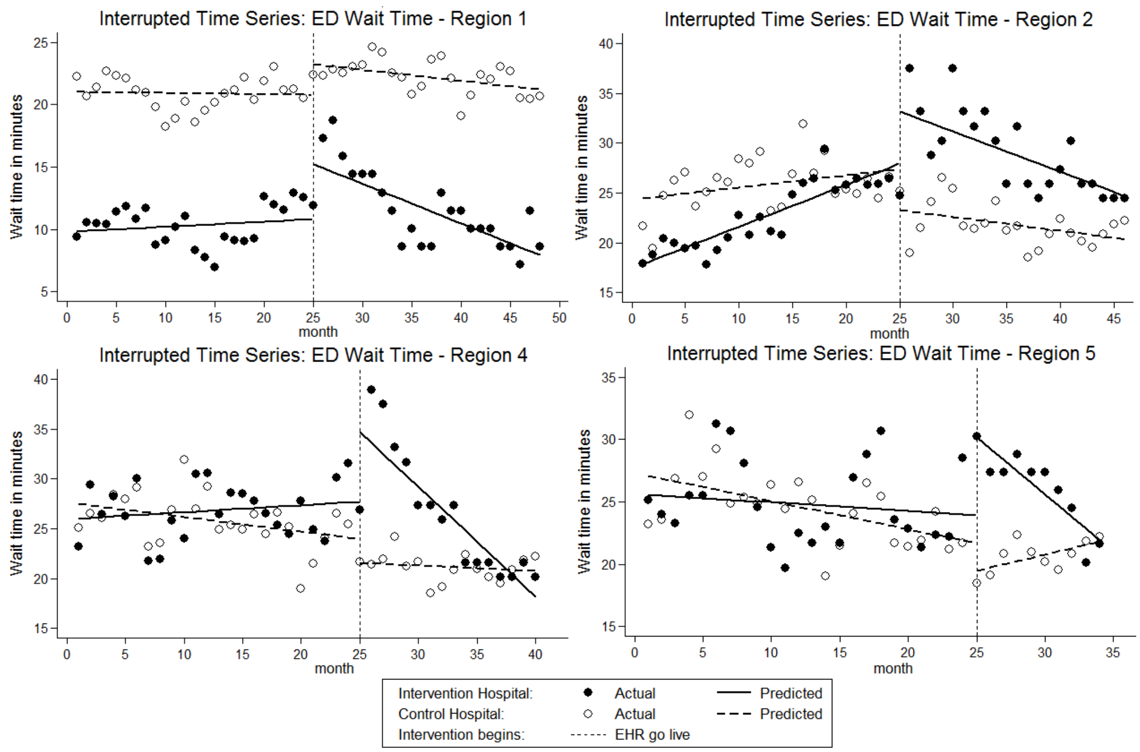

Figure 5.5 Emergency department wait time in all hospital regions.

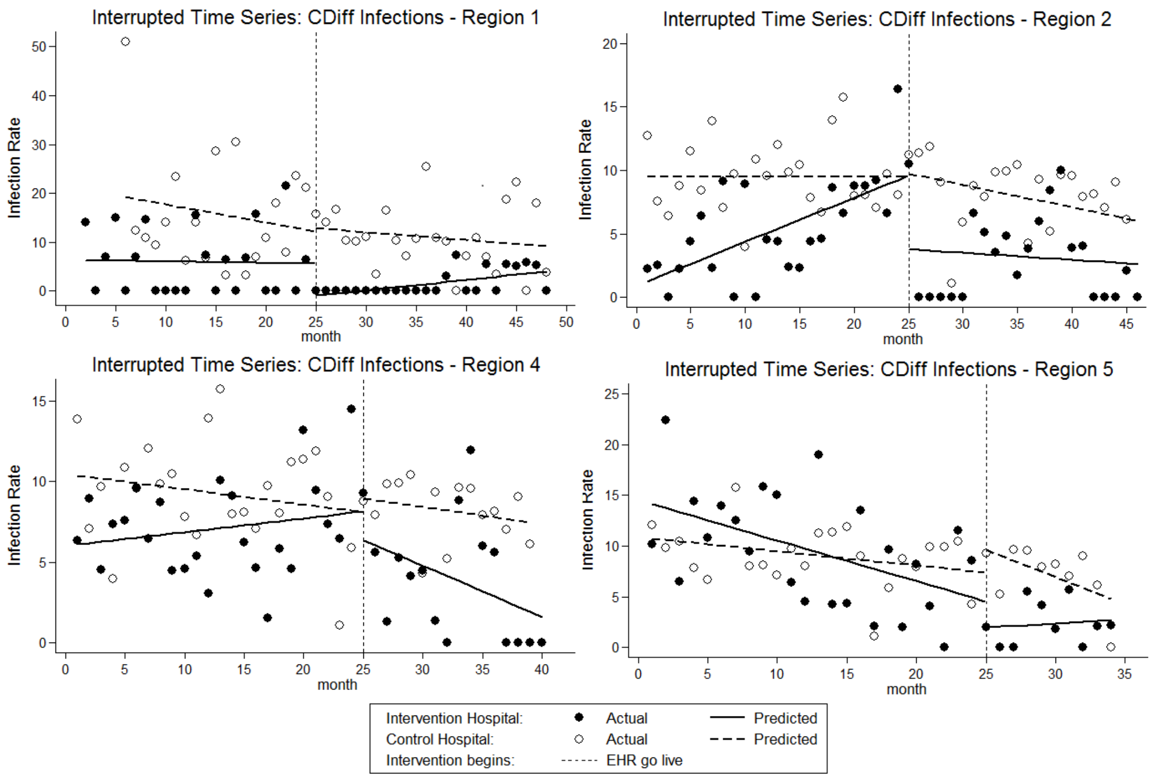

Figure 5.6 Hospital-acquired Clostridium Difficile infection rate in all hospital regions.

5.8 Supplementary Materials

Table 5S.1. Detailed setting characteristics

Characteristic	Region 1	Region 2	Region 3	Region 4	Region 5	Control
EHR Go live	Feb-15	Oct-15	Feb-16	Apr-16	Oct-16	Jul-17
Data collection period	02/2013 – 01/2017	10/2013 - 07/2017	02/2014 - 07/2017	04/2014 - 07/2017	10/2014 - 07/2017	02/2013 - 07/2017
Ambulatory care clinics	5	7	9	10	8	10
Ambulatory practice type[a]						
Primary care (n)	2	5	7	3	6	6
Mixed (n)	3	2	2	7	2	4
Ambulatory clinical setting						
Hospital-based	1	2	4	5	3	3
Non-hospital-based	4	5	5	5	5	7
Ambulatory visits, M (SD)[b]	1543 (113)	2239 (191)	611 (50)	971 (81)	1704 (132)	1186 (147)
Hospital size						
Medium (100 - 399 beds)	1	1	-	1	1	1
Large ($\geq$ 400 beds)	-	-	-	-	-	1
Teaching status						
Academic	-	-	-	-	-	-
Non-academic	1	1	-	1	1	2
Medium hospital admissions, M (SD)[c]	752 (49)	1792 (113)	-	1923 (143)	1544 (91)	1055(56)
Large hospital admissions, M (SD)[c]	-	-	-	-	-	2517 (130)

Notes: EHR: electronic health record; M: Mean; SD: standard deviation.

[a] Primary care settings include the specialties Family Medicine, Internal Medicine, and/or Pediatrics; Mixed settings include any of the three previous primary care specialties and other secondary specialties.

[b] Denotes average visits per month for the whole study period calculated by combining all clinics within each region.

[c] Denotes average admissions per month for the whole study period for each hospital in each region.

Table 5S.2. 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 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 of employee contracts terminated	N: ambulatory employees with voluntary contract termination D: total ambulatory employees
Laboratory orders	Number of orders of laboratory tests	Number of orders of laboratory tests
New patient visits	Rate of new patient 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 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

Notes: N: numerator; D: denominator.

Table 5S.3. 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 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 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 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 orders	Number of orders of laboratory tests	Number of orders of laboratory tests
Radiology 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

Table 5S.3. Continued

Measure	Description	Criteria
Productivity measures		
Time to complete radiology tests	Mean time between radiology test started and completed	Mean time between patient arrival and imaging test completed
Time to sign radiology tests	Mean time between radiology test completed and report issued by radiologist	Mean time for issuing imaging test report
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: 10000 inpatient days
Hospital-acquired CRA infection rate	Rate of hospital-acquired infections caused by Carbapenem-resistant Acinetobacter	N: CRA infections D: 10000 inpatient days
Hospital-acquired infection MRSA rate	Rate of hospital-acquired infections caused by Methicillin-resistant Staphylococcus aureus	N: MRSA infections D: 10000 inpatient days
Hospital-acquired VRE infection rate	Rate of hospital-acquired infections caused by Vancomycin-resistant Enterococci	N: VRE infections D: 10000 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

Notes: N: numerator; D: denominator.

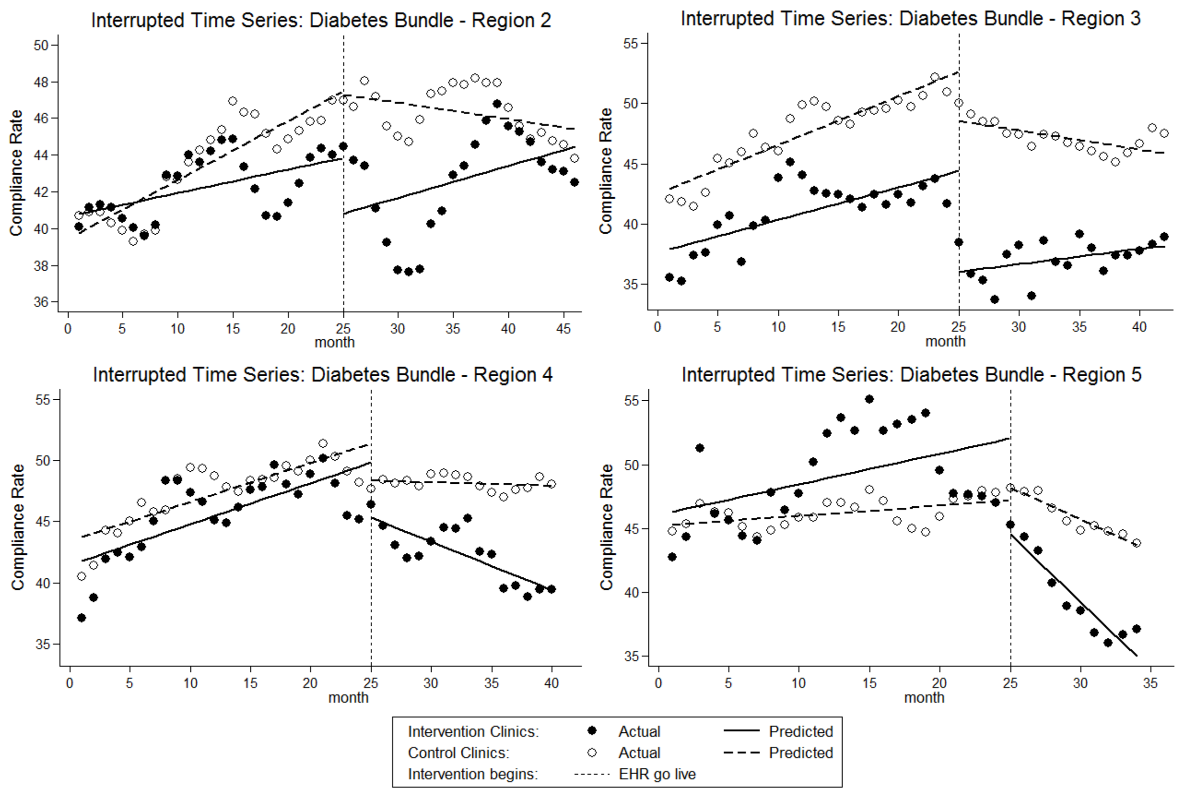

Figure 5S.1. Diabetes bundle compliance in ambulatory clinics before and after EHR go live

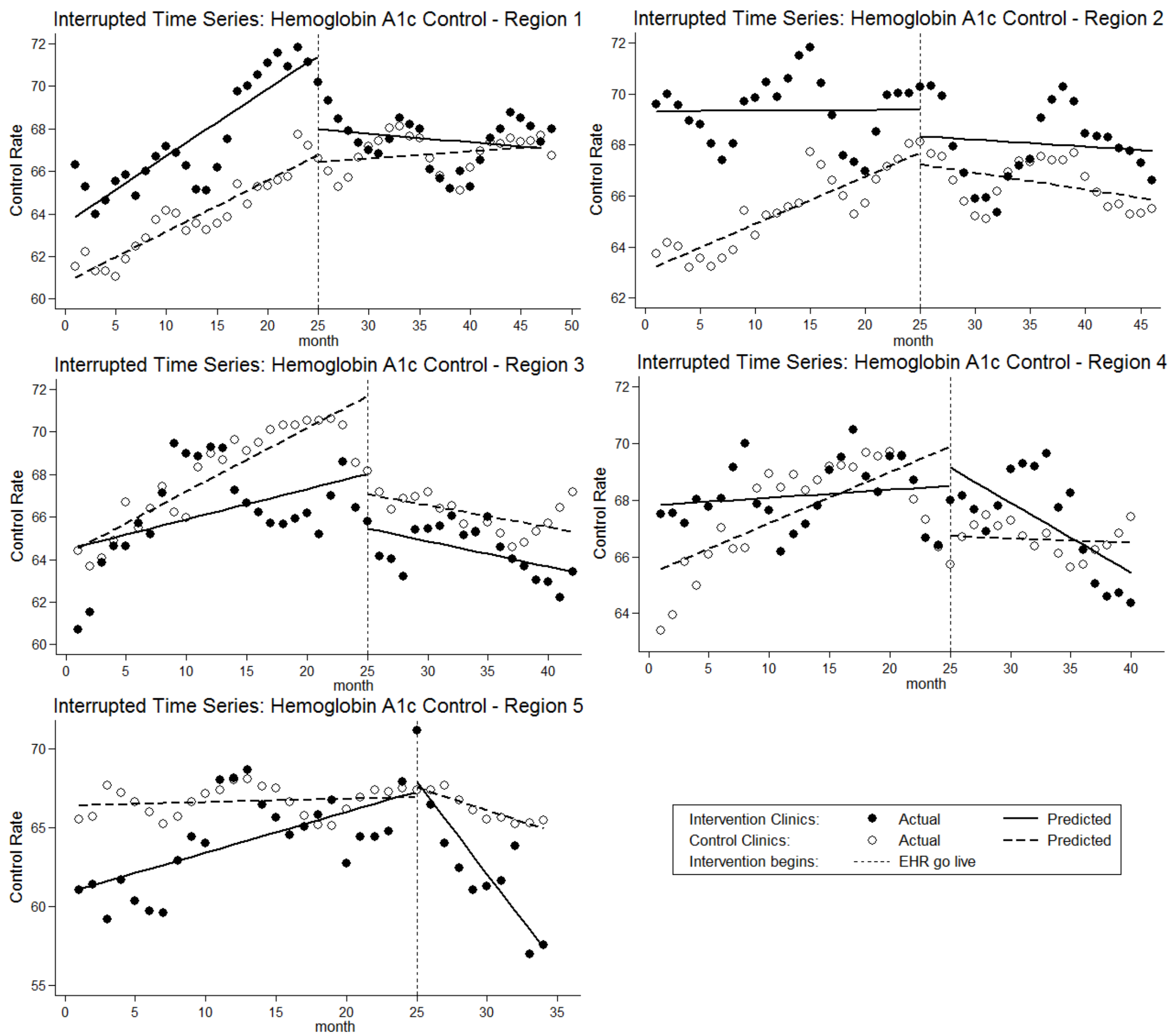

Figure 5S.2. Hemoglobin A1c control in ambulatory clinics before and after EHR go live

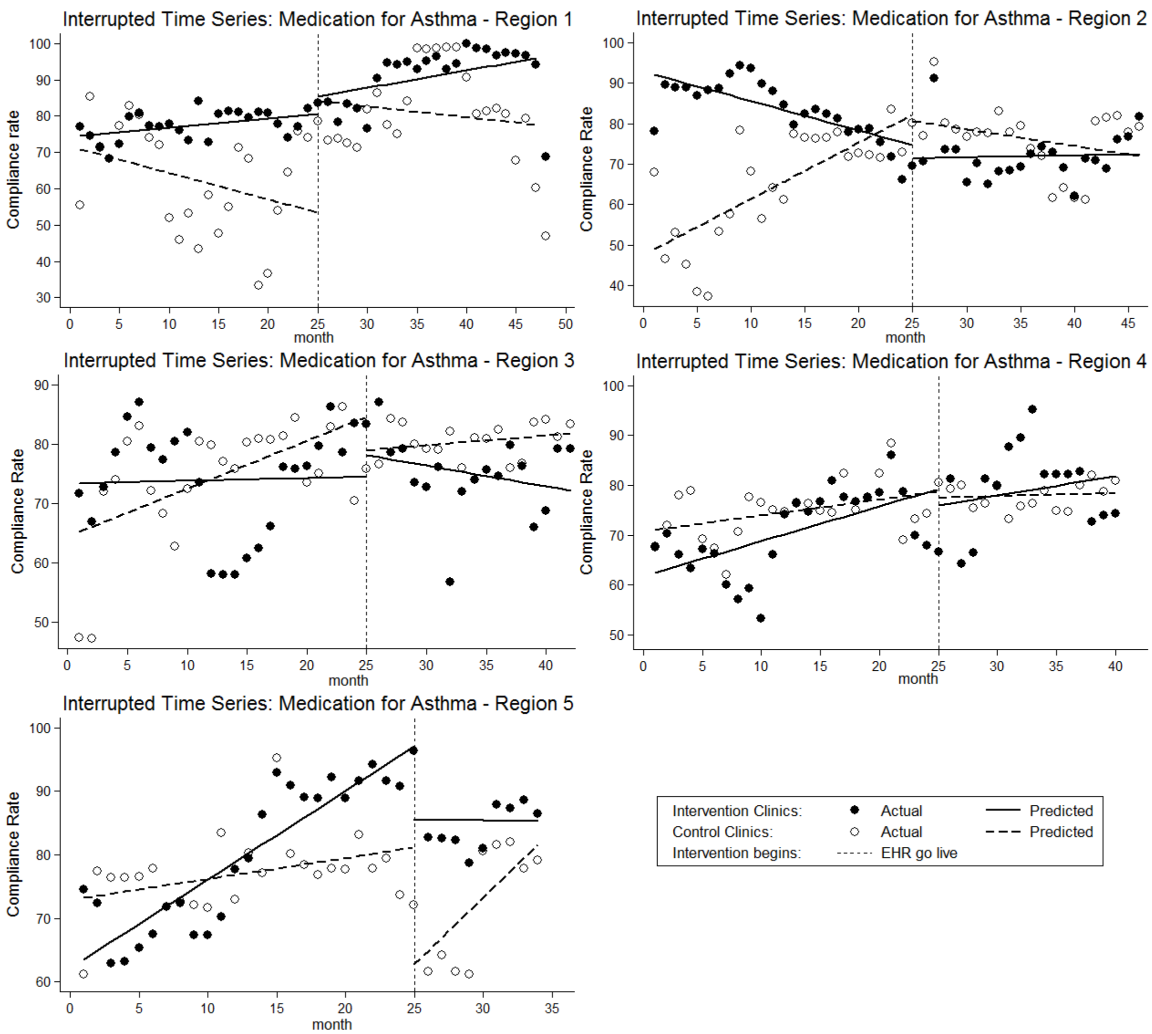

Figure 5S.3. Medication for asthma compliance in ambulatory clinics before and after EHR go live

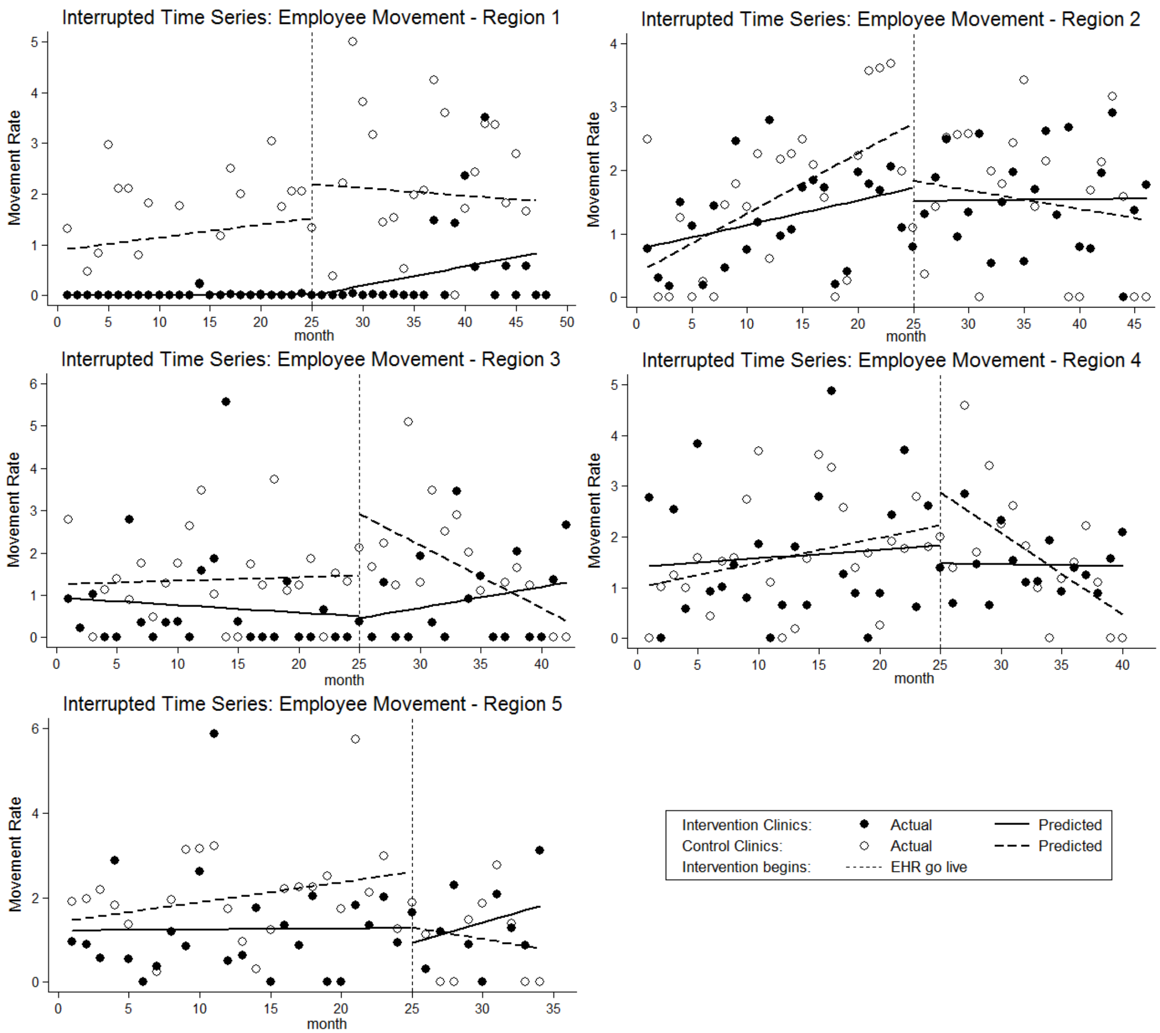

Figure 5S.4. Employee movement rate in ambulatory clinics before and after EHR go live

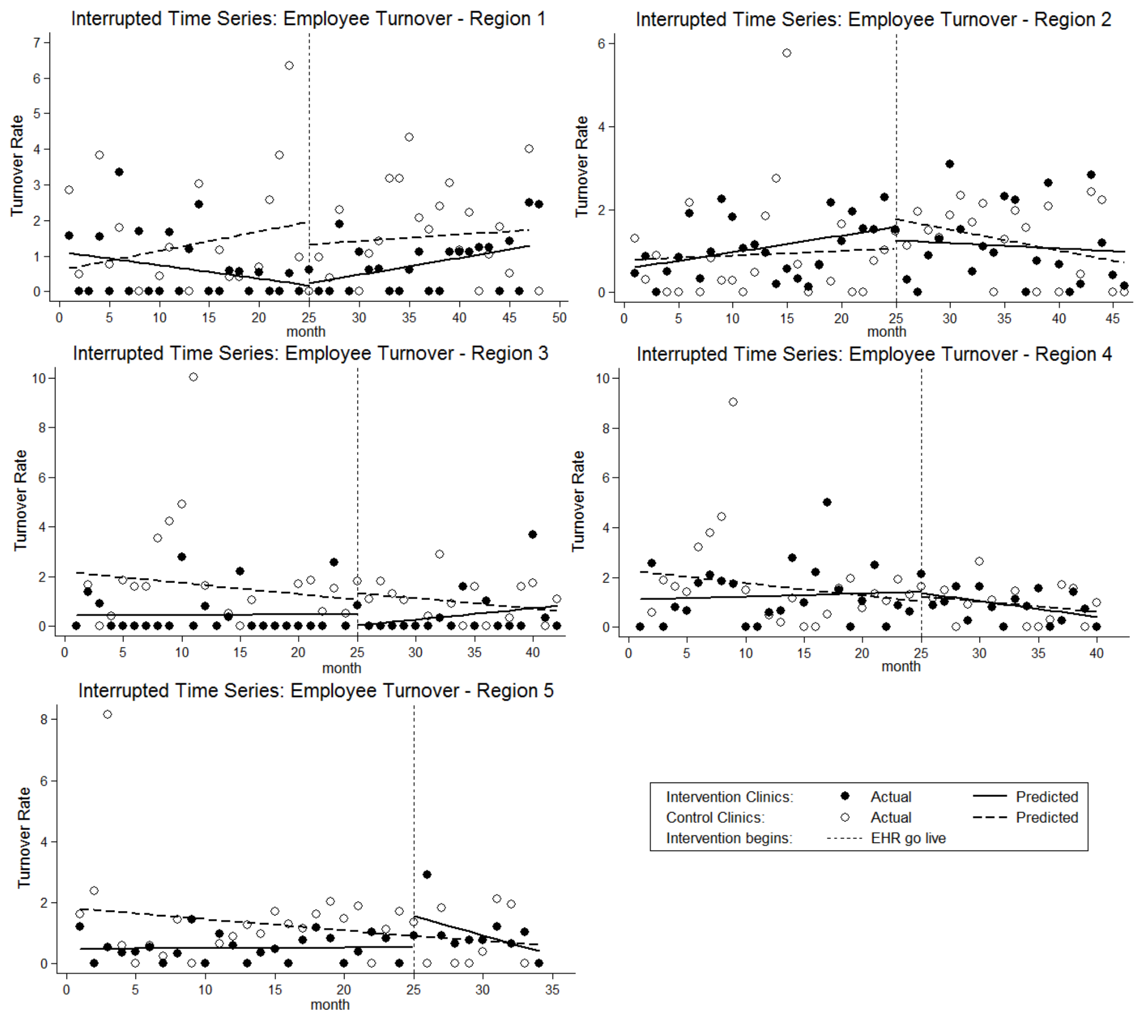

Figure 5S.5. Employee turnover rate in ambulatory clinics before and after EHR go live

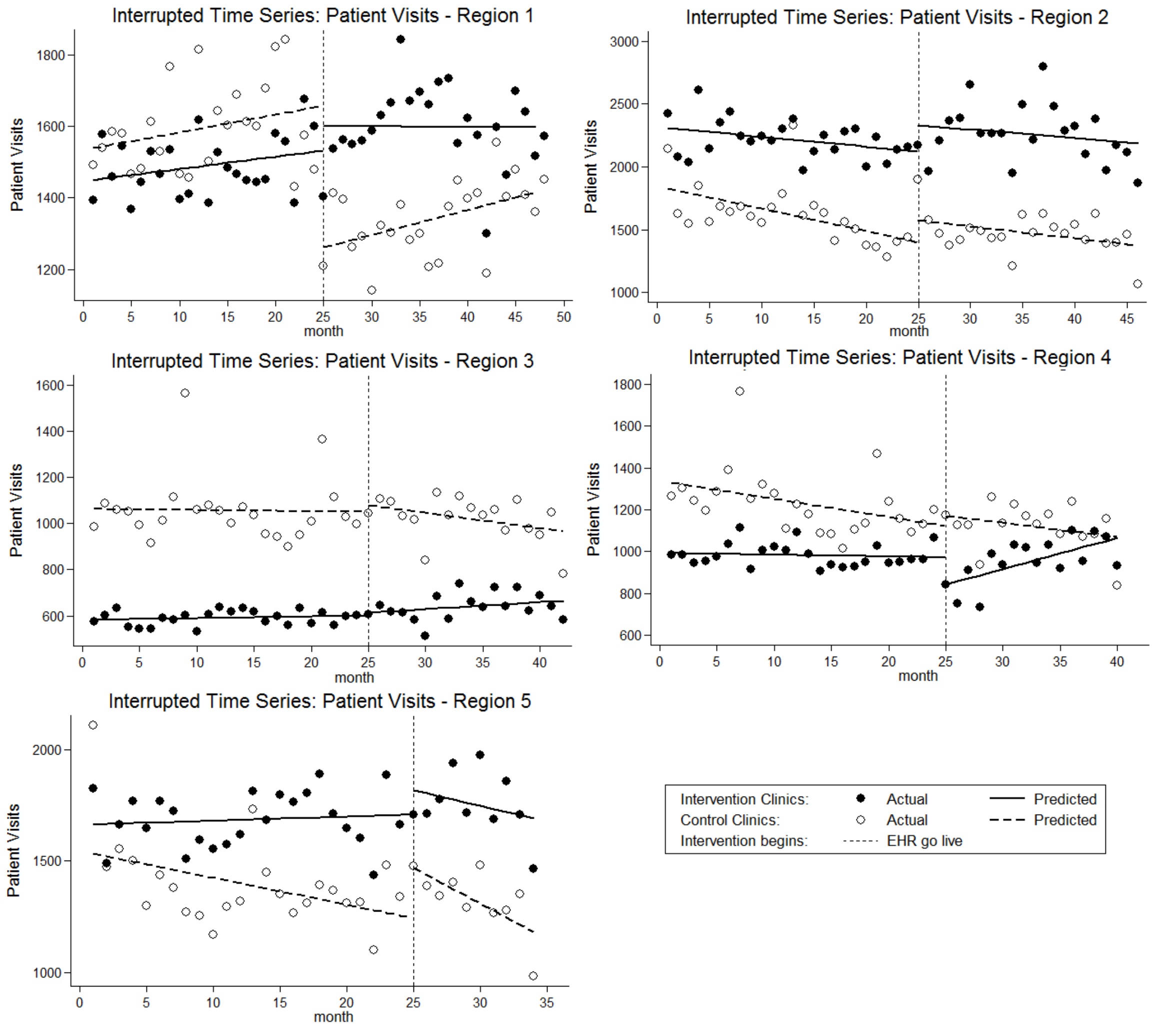

Figure 5S.6. Patient visits in ambulatory clinics before and after EHR go live

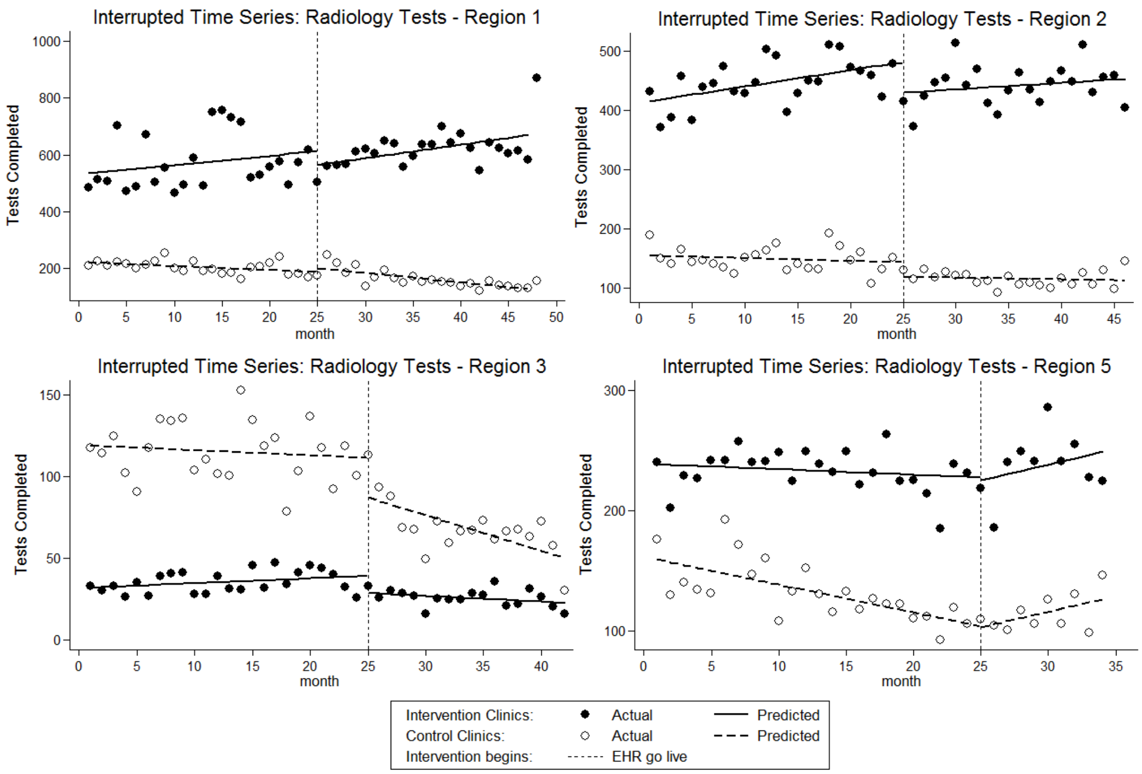

Figure 5S.7. Radiology orders in ambulatory clinics before and after EHR go live

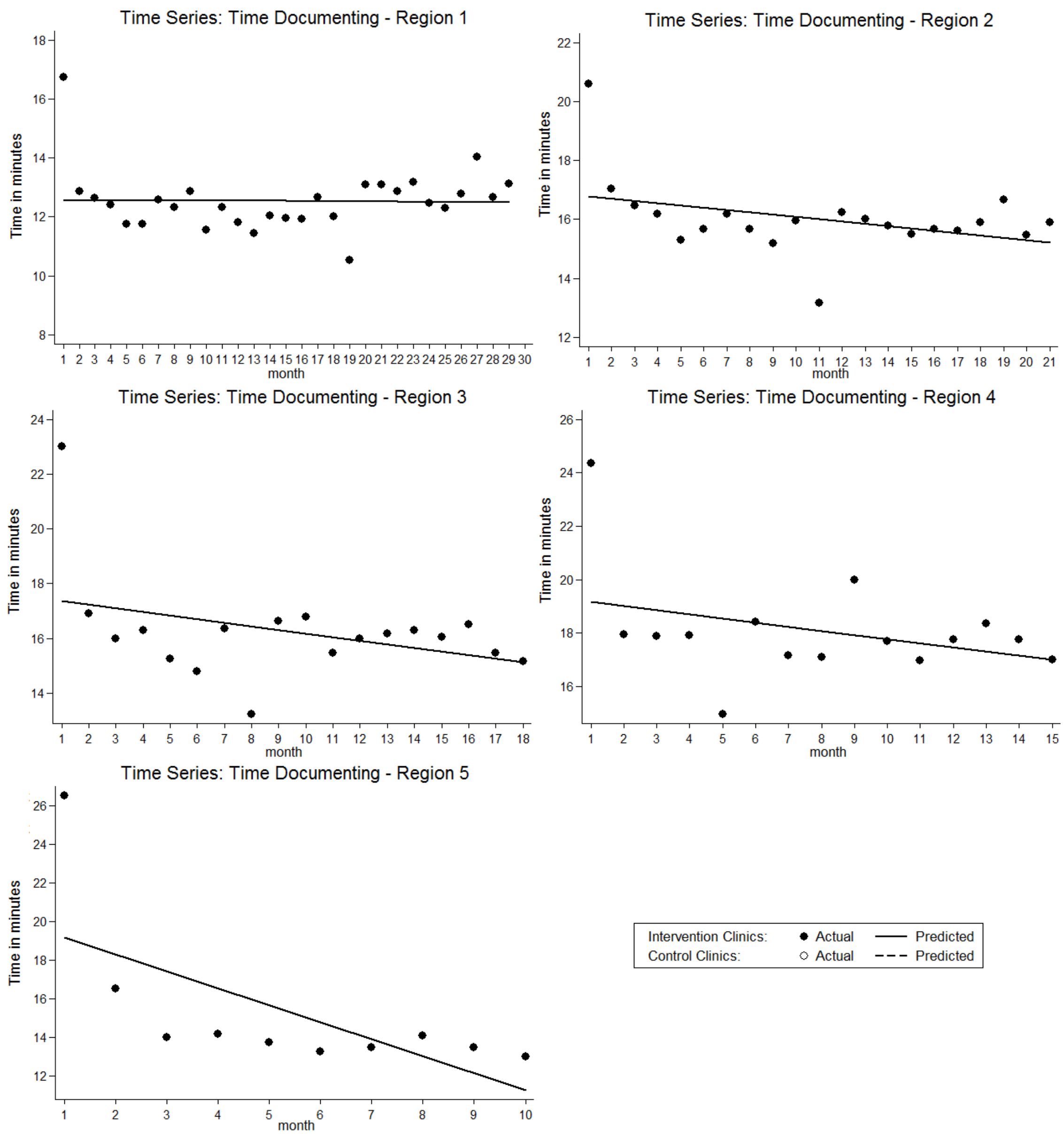

Figure 5S.8. Time documenting in EHR in ambulatory clinics before and after EHR go live

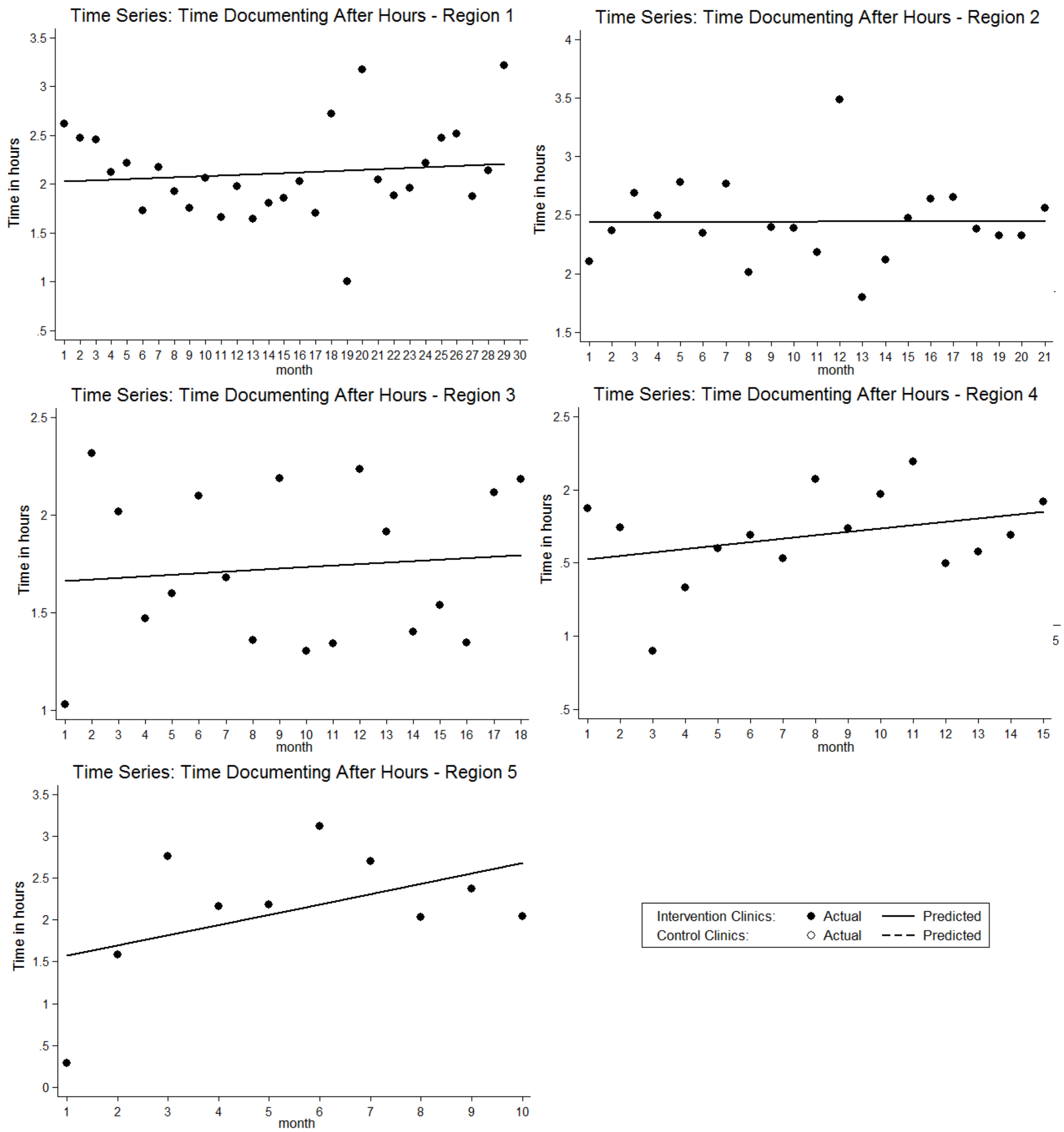

Figure 5S.9. Time documenting in EHR after hours in ambulatory clinics before and after EHR go live

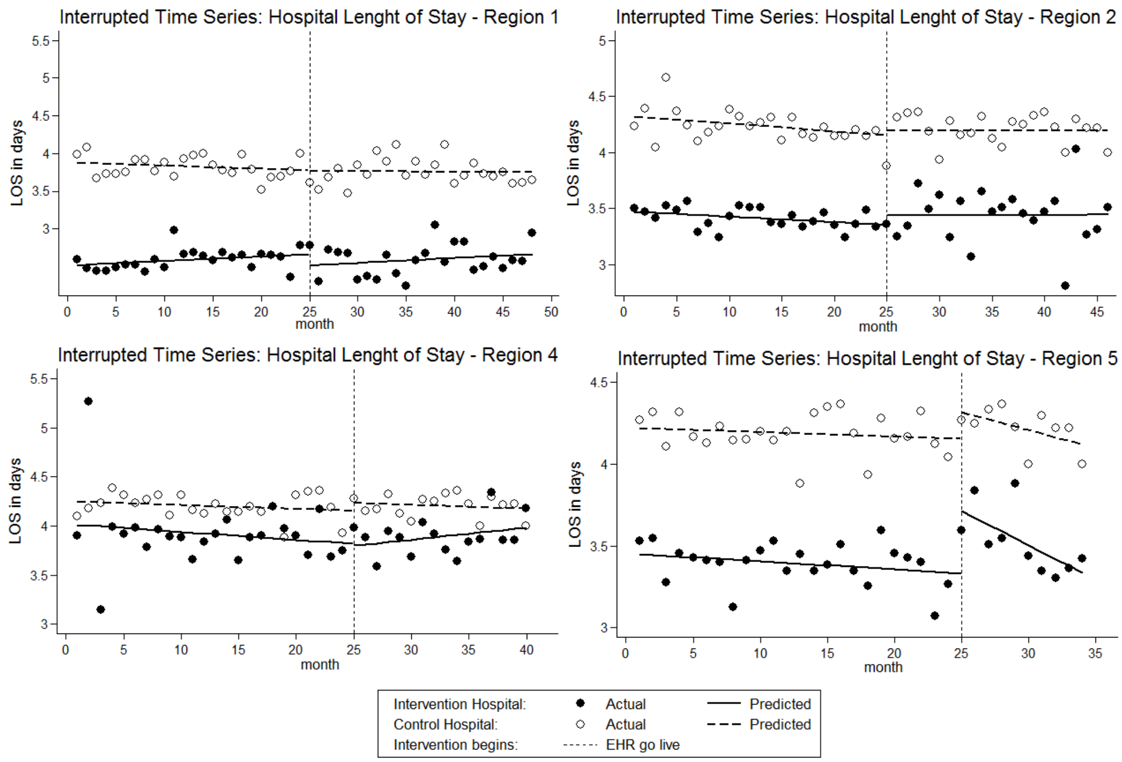

Figure 5S.10. Hospital length of stay before and after EHR go live

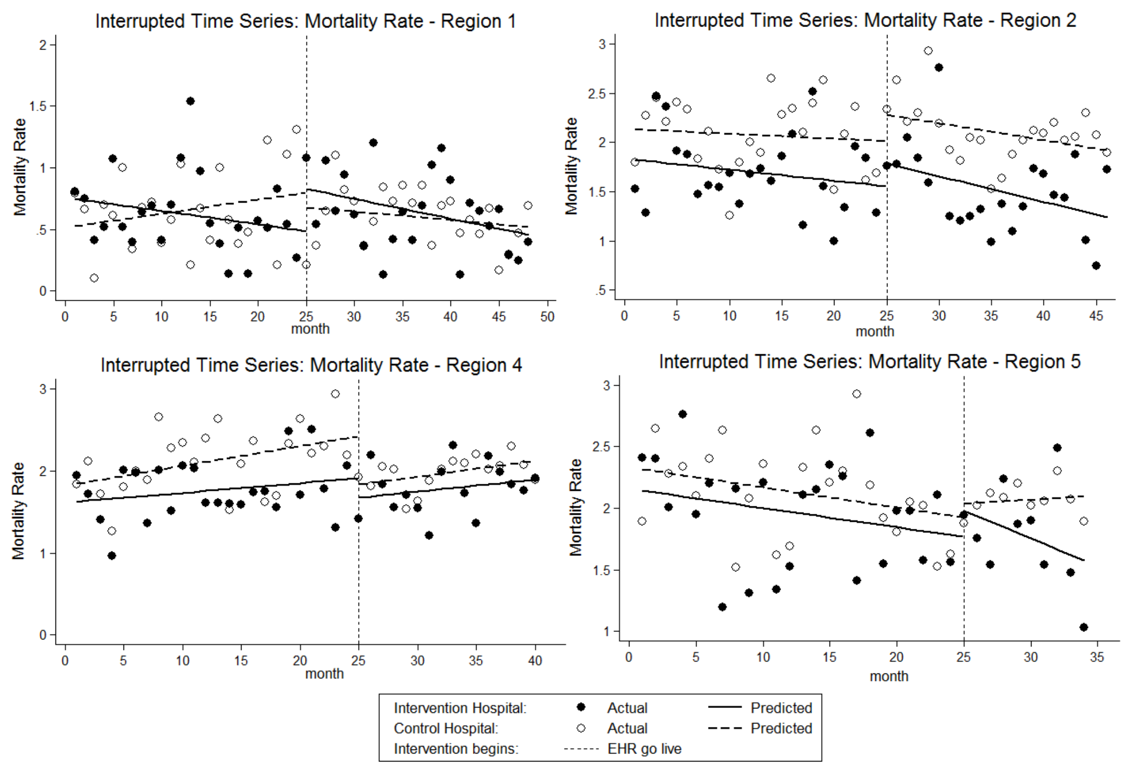

Figure 5S.11. Mortality rate in hospital settings before and after EHR go live

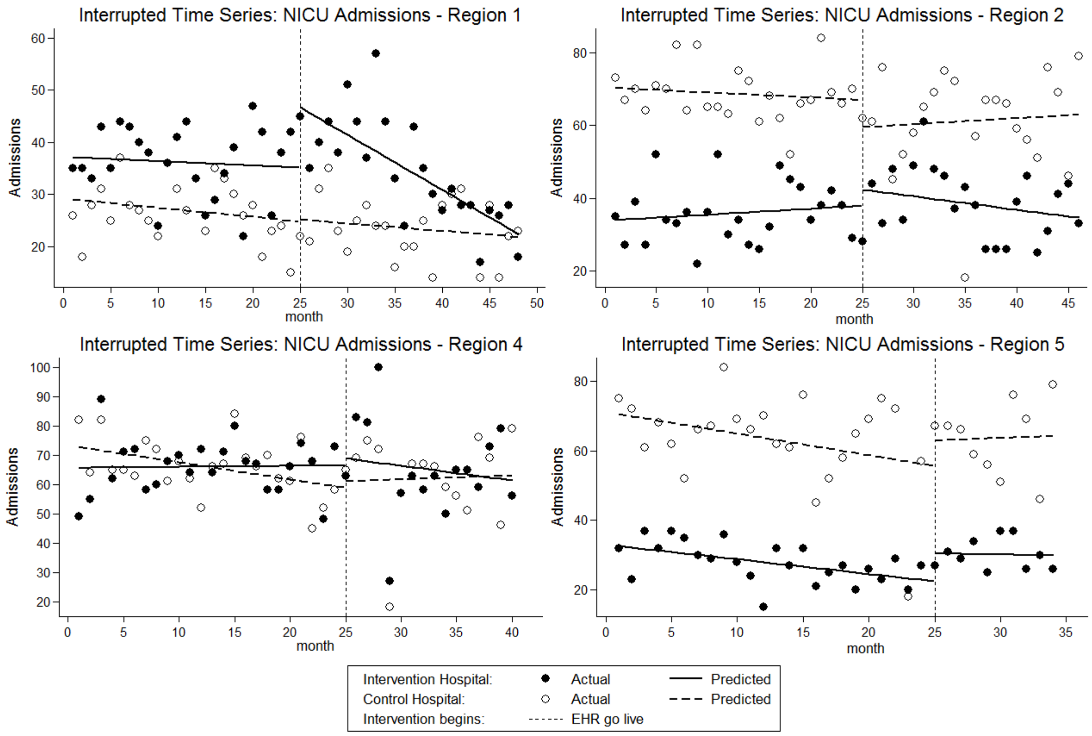

Figure 5S.12. Newborn intensive care unit admissions before and after EHR go live

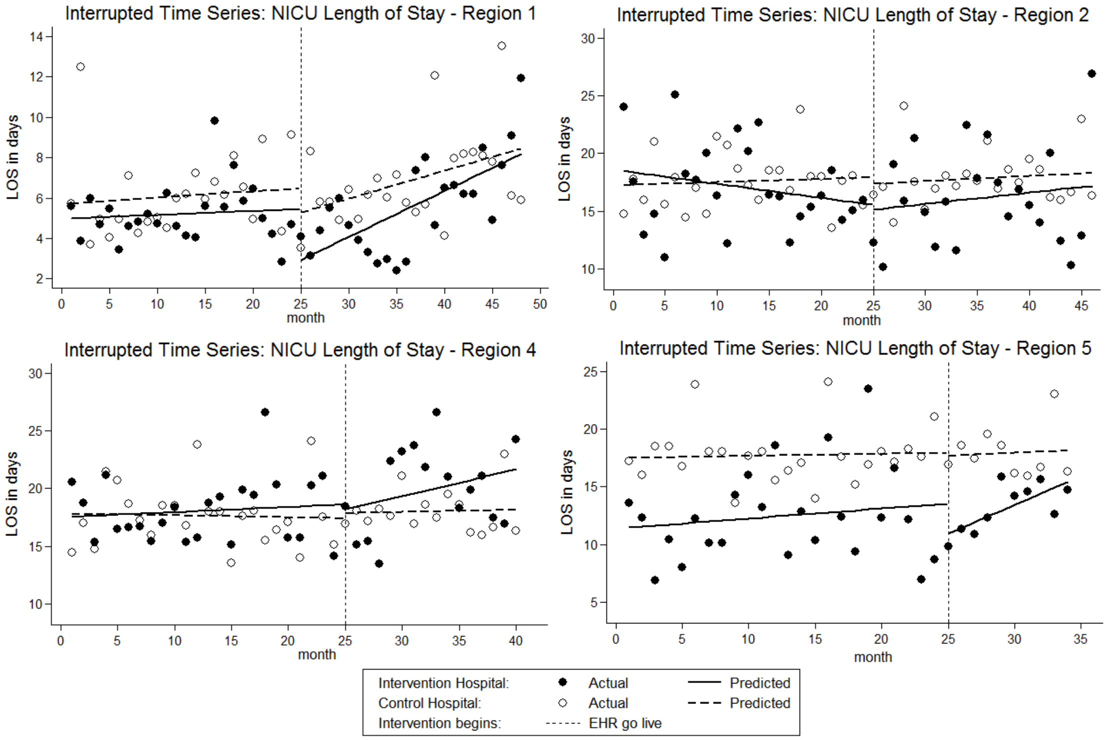

Figure 5S.13. Newborn intensive care unit length of stay before and after EHR go live

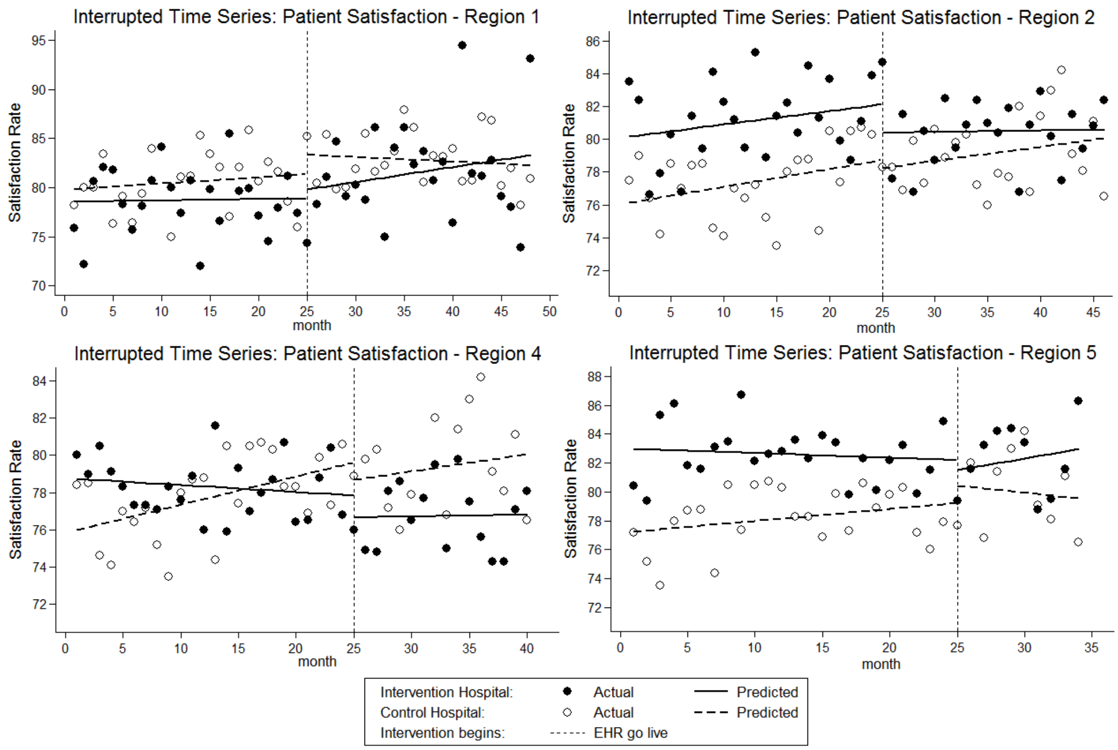

Figure 5S.14. Patient satisfaction in hospital settings before and after EHR go live

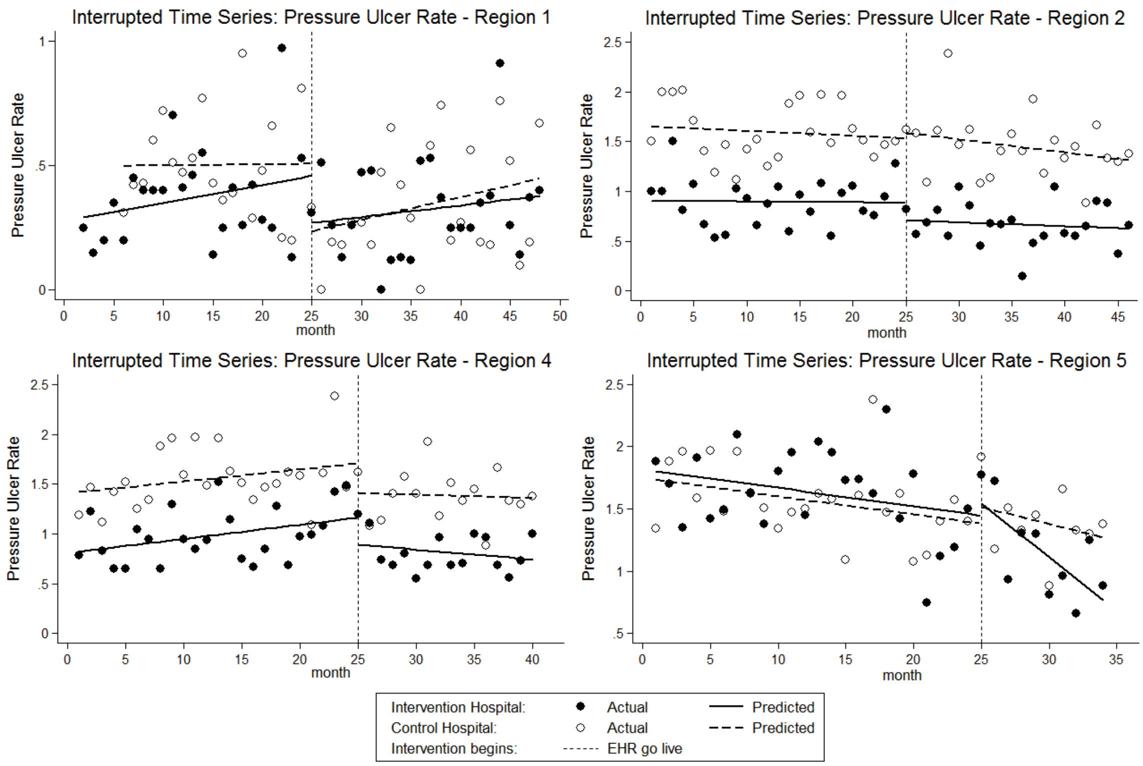

Figure 5S.15. Pressure ulcer rate before and after EHR go live

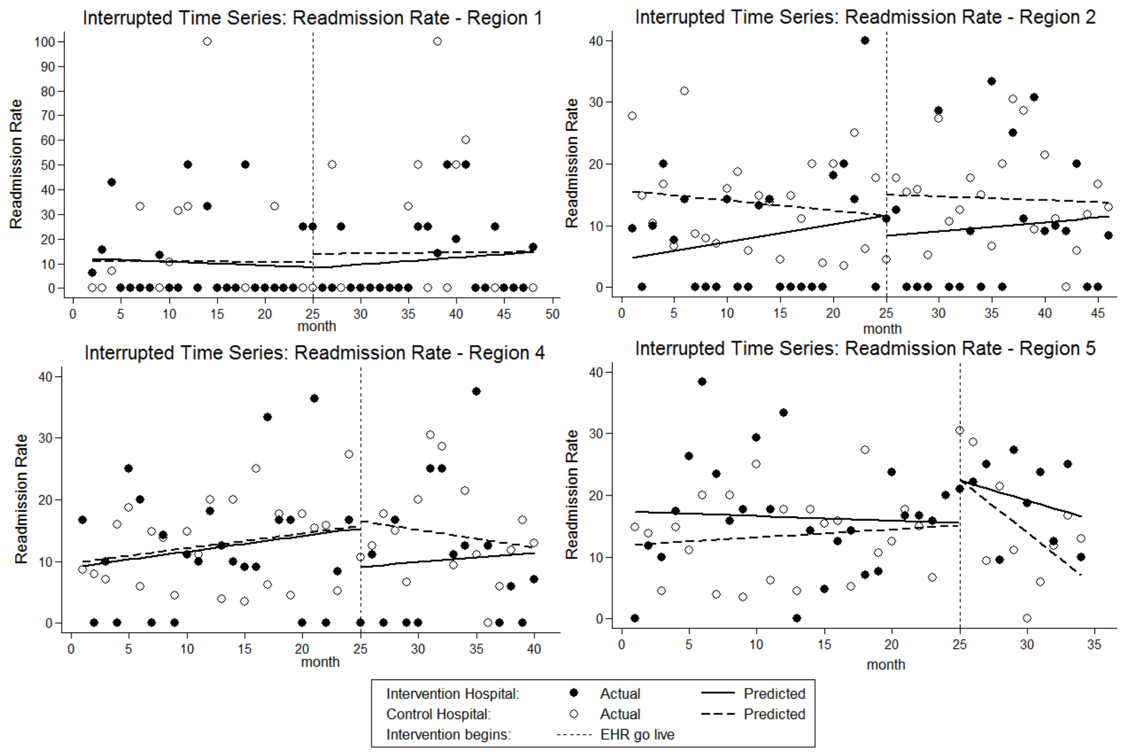

Figure 5S.16. Readmission rate before and after EHR go live

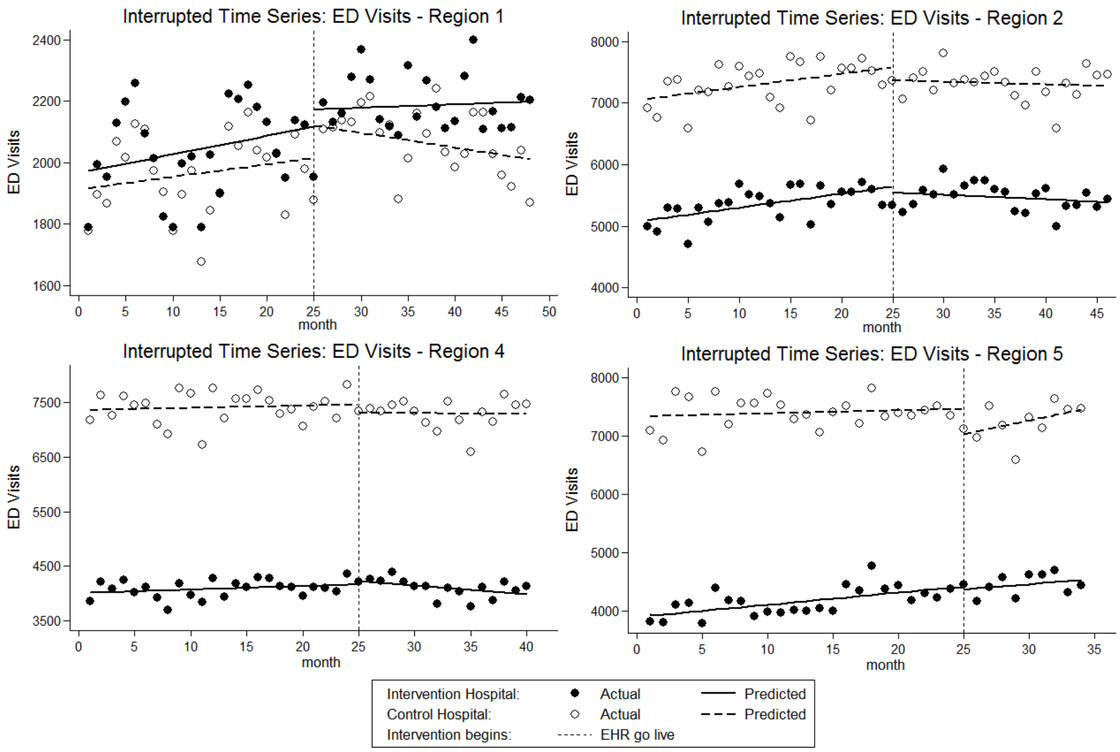

Figure 5S.17. Emergency department visits before and after EHR go live

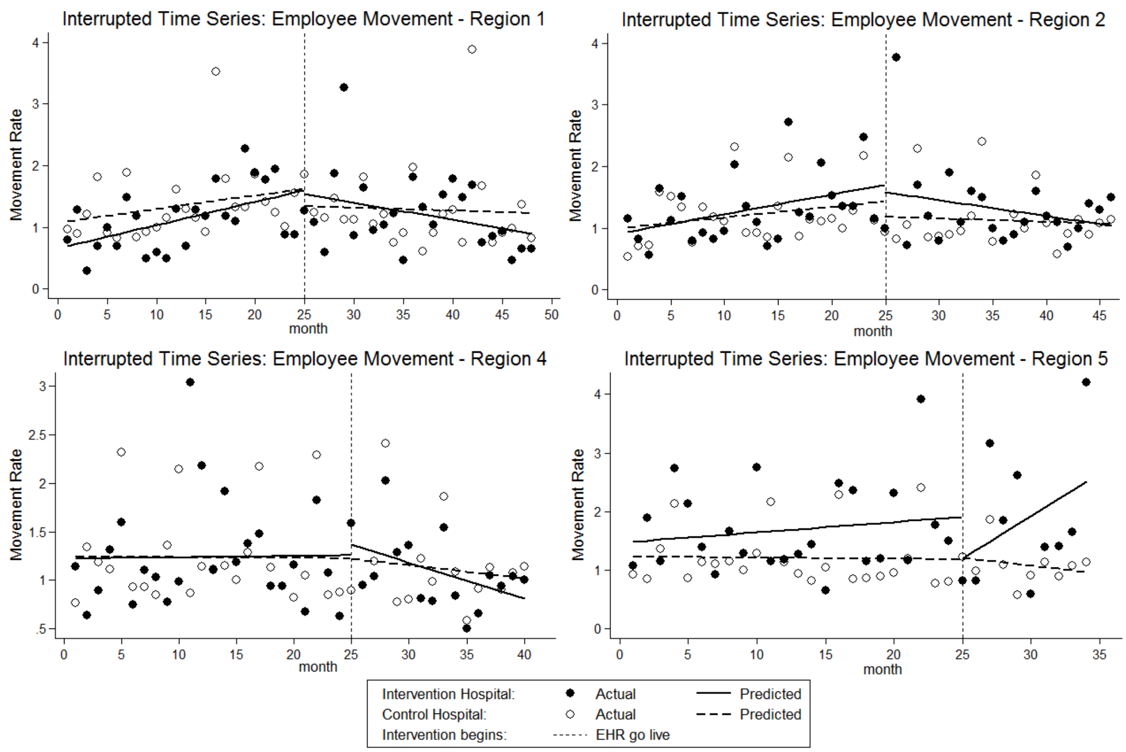

Figure 5S.18. Employee movement before and after EHR go live

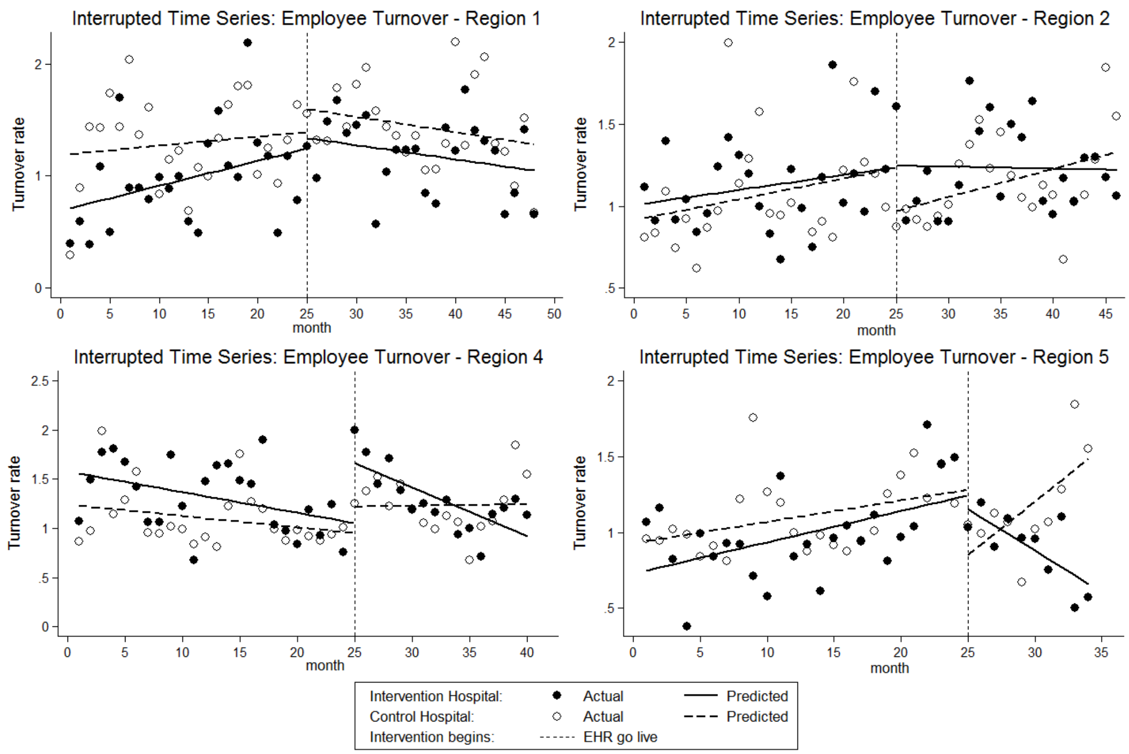

Figure 5S.19. Employee turnover before and after EHR go live

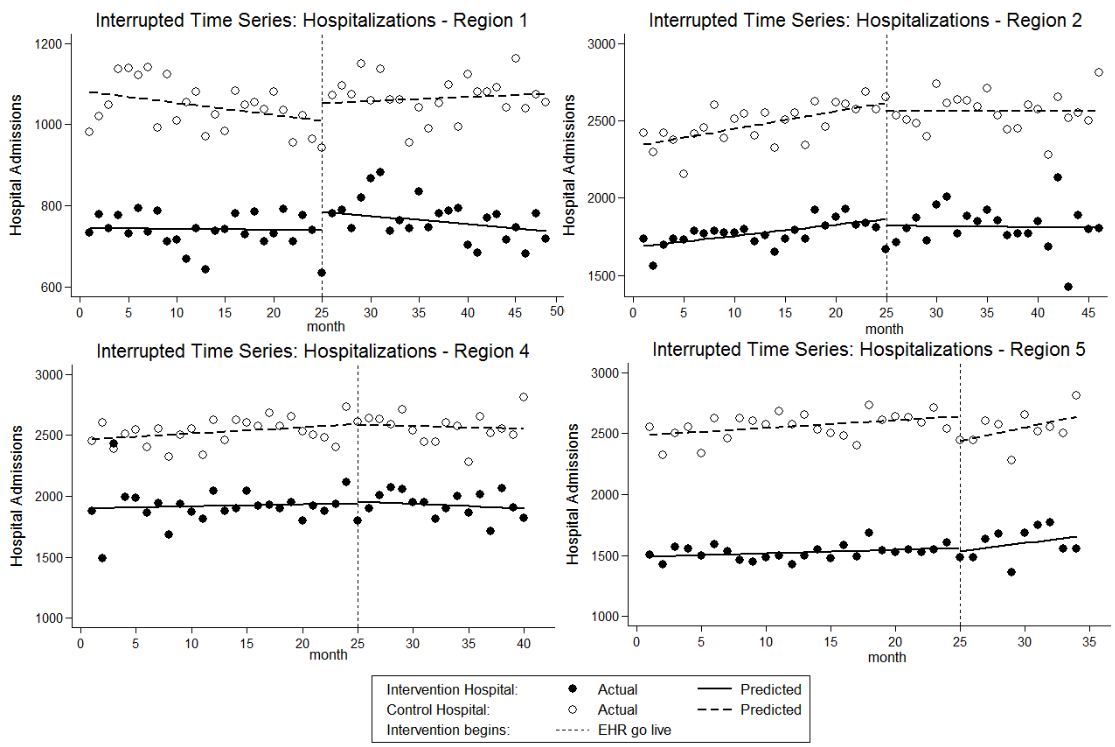

Figure 5S.20. Hospitalizations before and after EHR go live

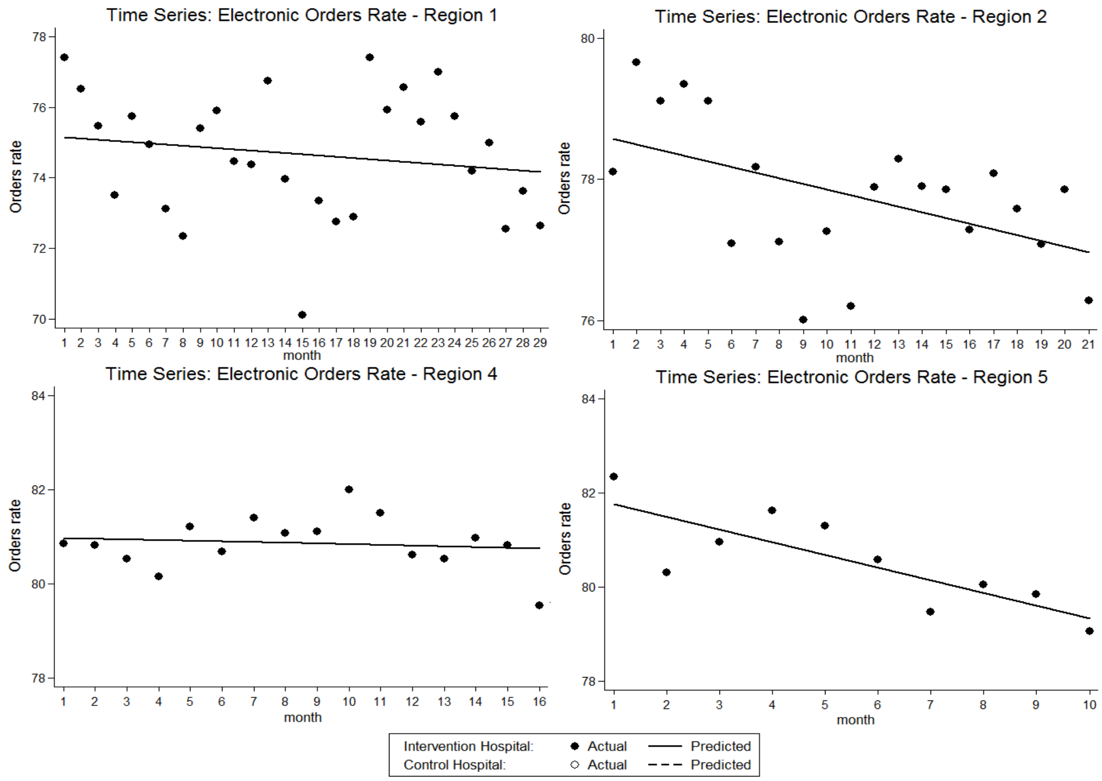

Figure 5S.21. Electronic orders rate in hospital settings before and after EHR go live

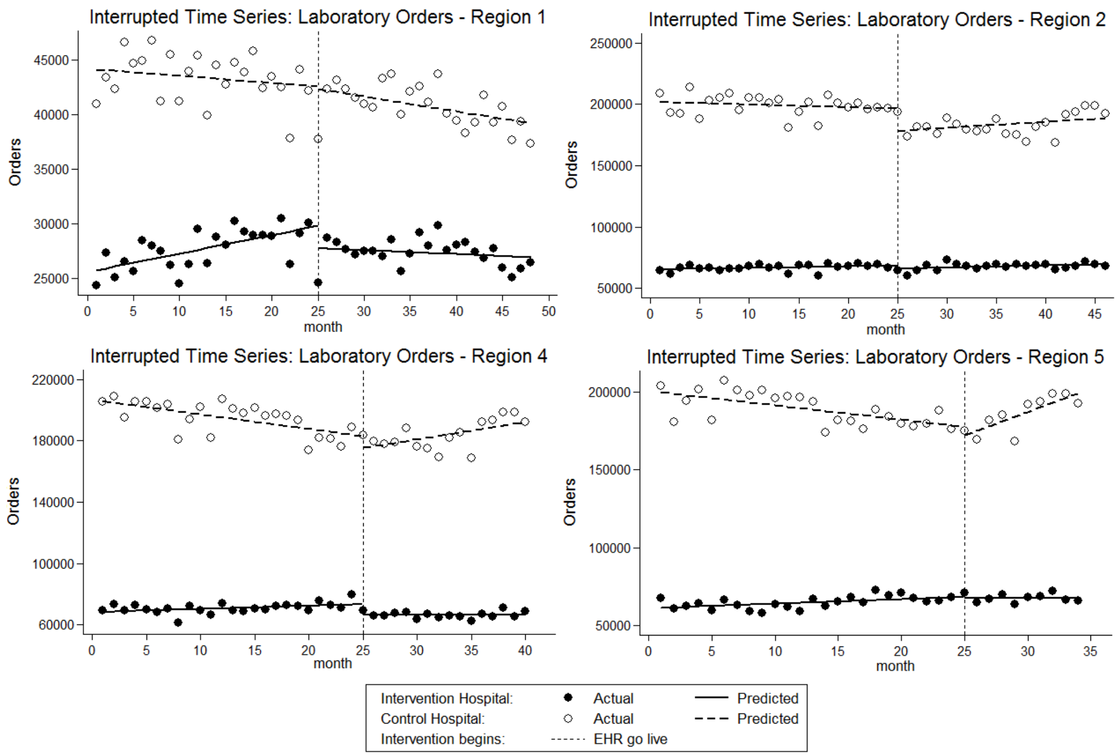

Figure 5S.22. Laboratory orders in hospital settings before and after EHR go live

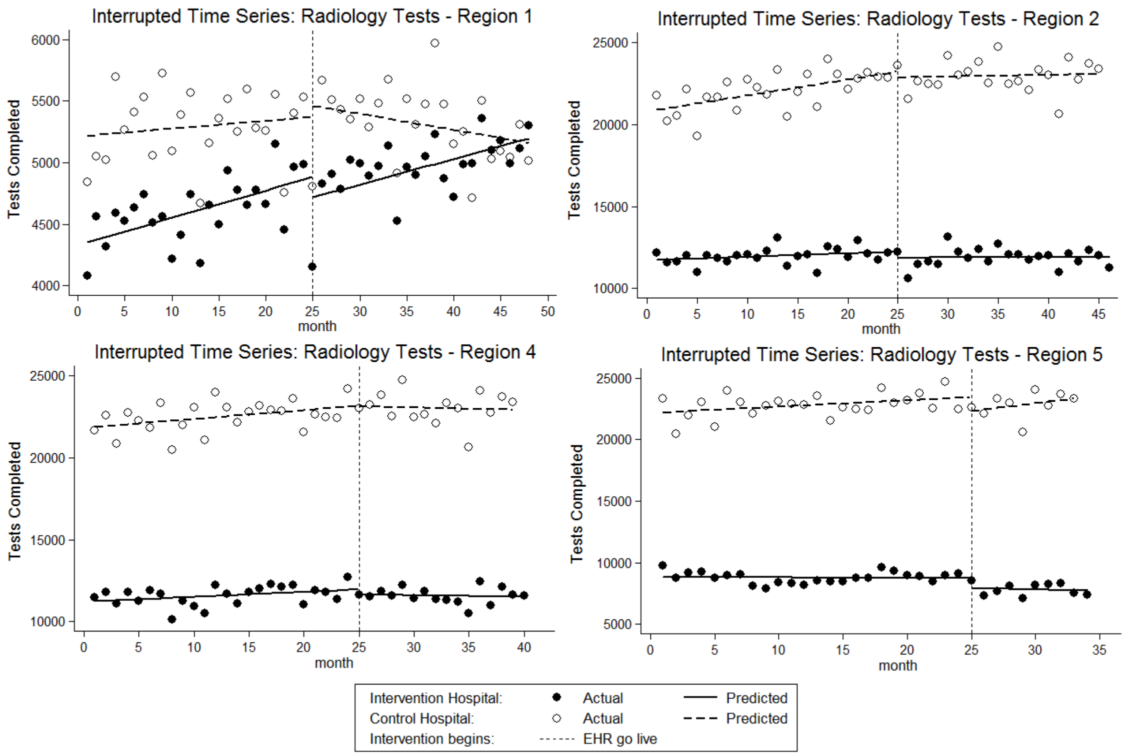

Figure 5S.23. Radiology orders in hospital settings before and after EHR go live

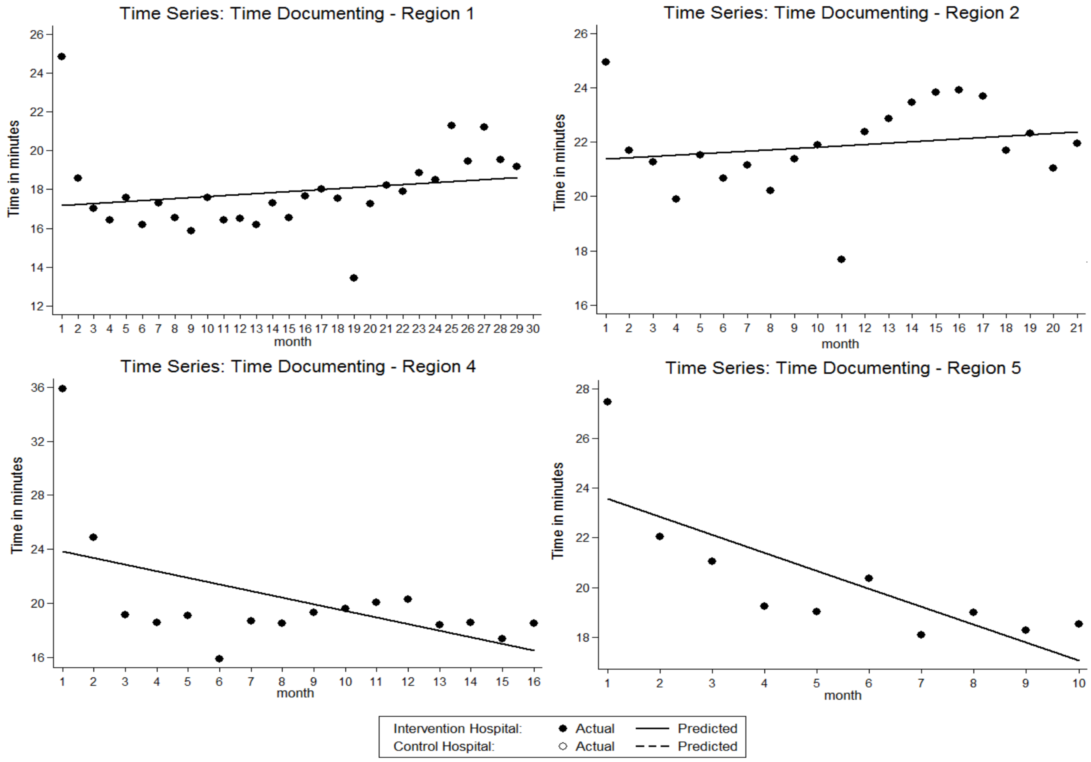

Figure 5S.24. Time documenting in EHR in hospital settings before and after EHR go live

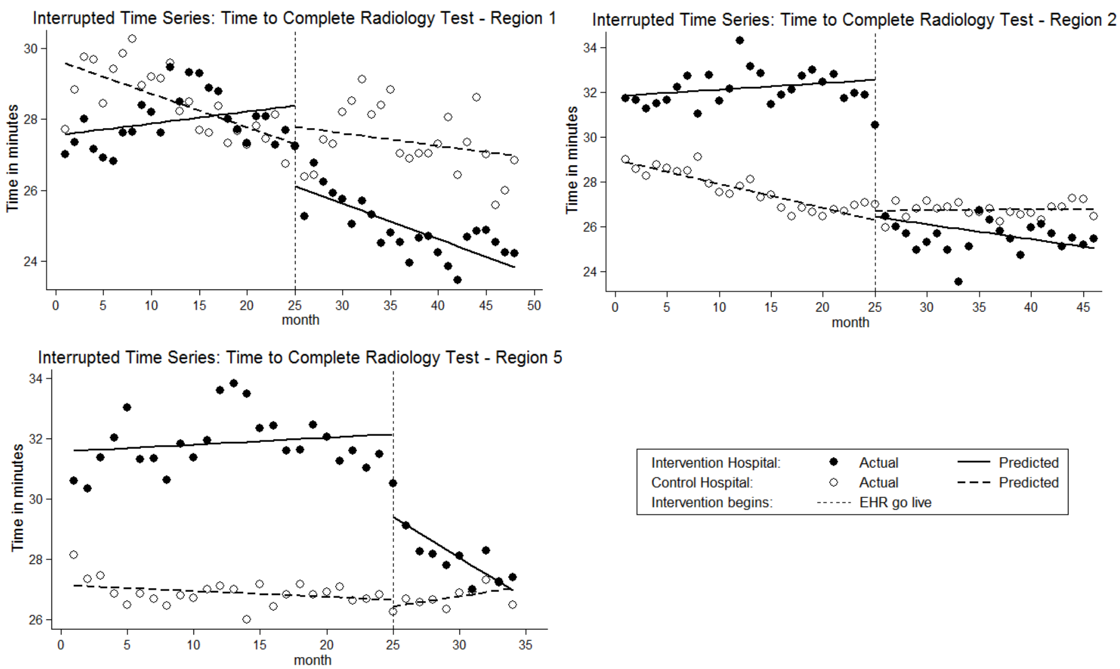

Figure 5S.25. Time to complete radiology tests in hospital settings before and after EHR go live

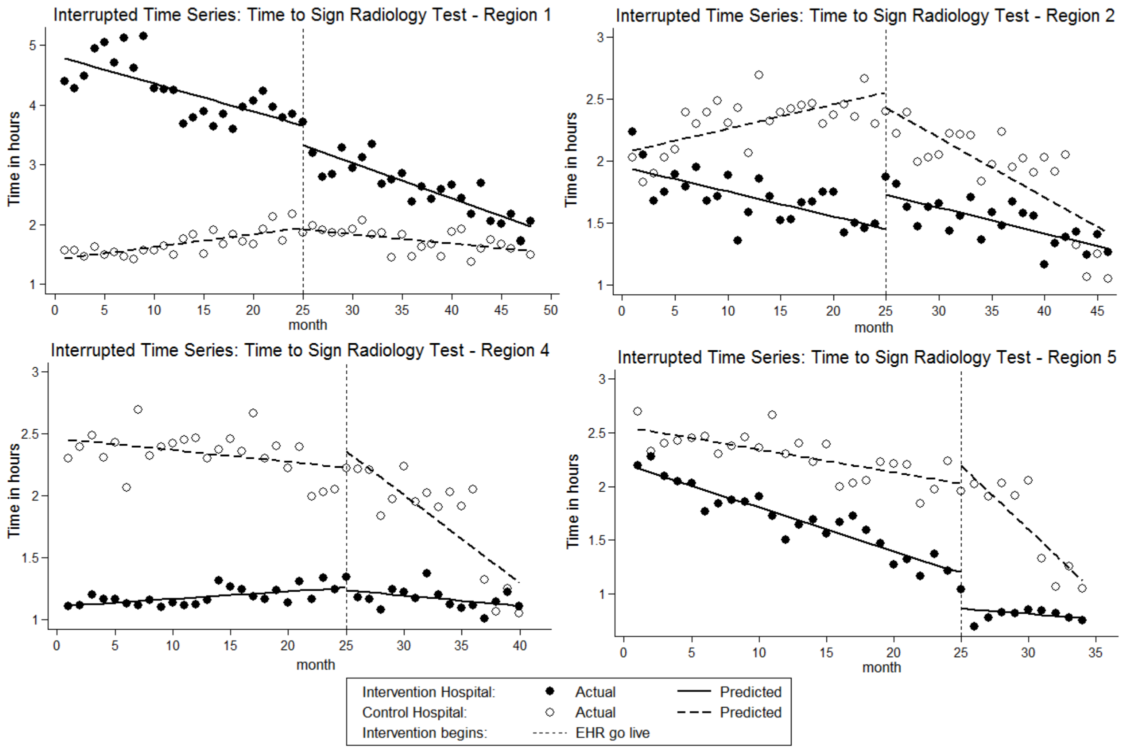

Figure 5S.26. Time to sign radiology tests in hospital settings before and after EHR go live

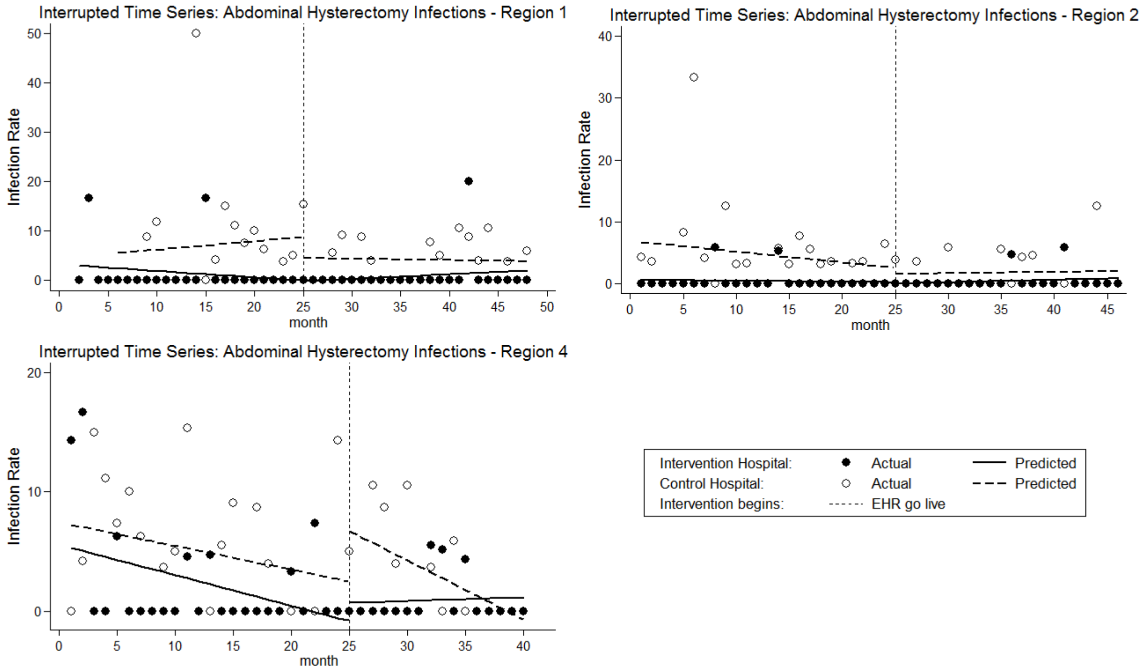

Figure 5S.27. Abdominal hysterectomy infection rate in hospital settings before and after EHR go live

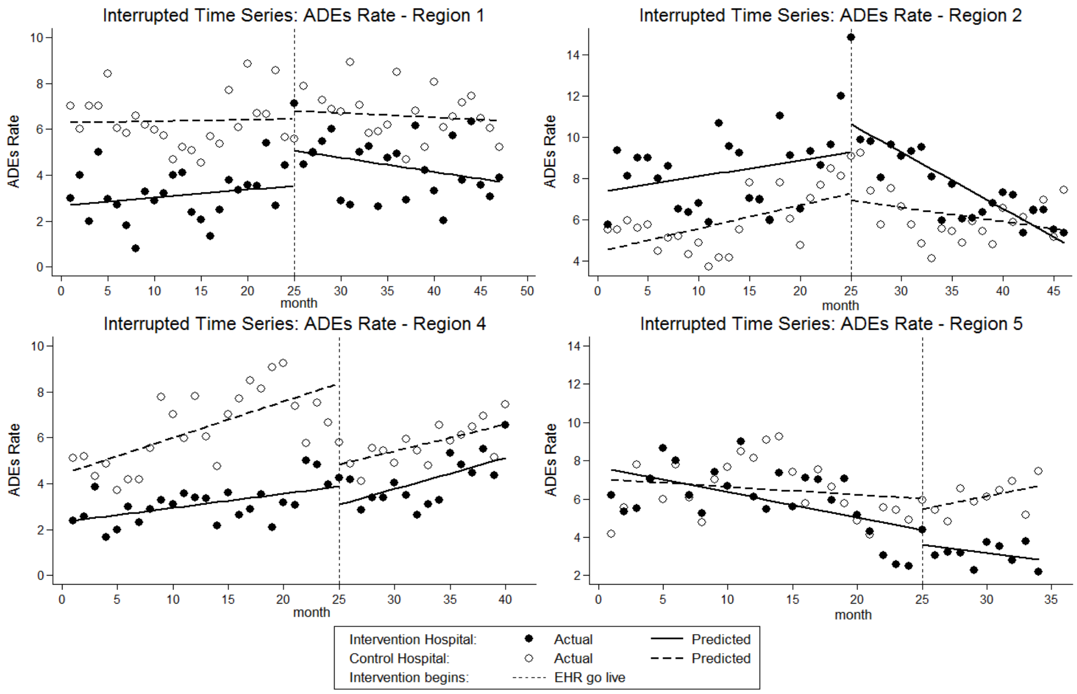

Figure 5S.28. Adverse drug events rate in hospital settings before and after EHR go live

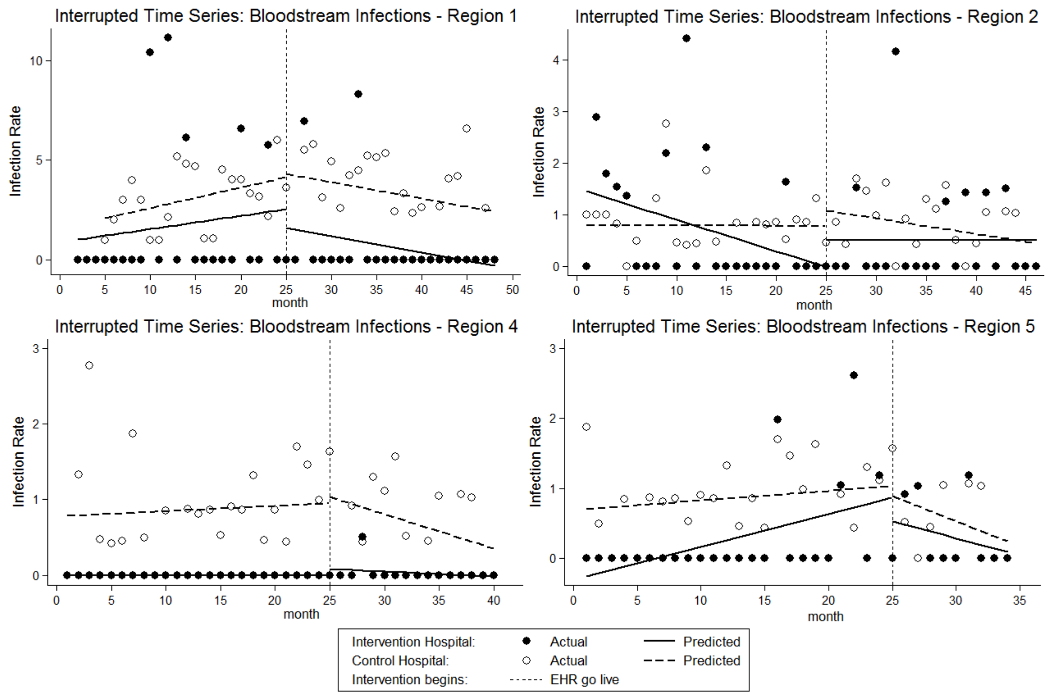

Figure 5S.29. Bloodstream infection rate in hospital settings before and after EHR go live

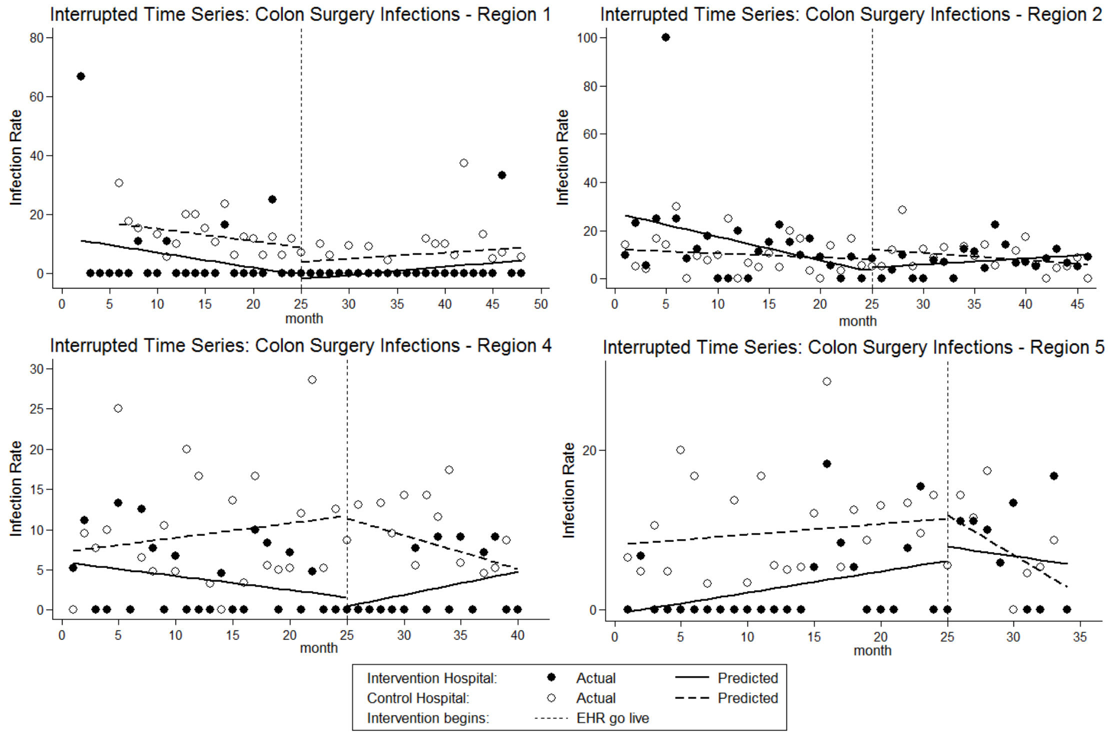

Figure 5S.30. Colon surgery infection rate in hospital settings before and after EHR go live

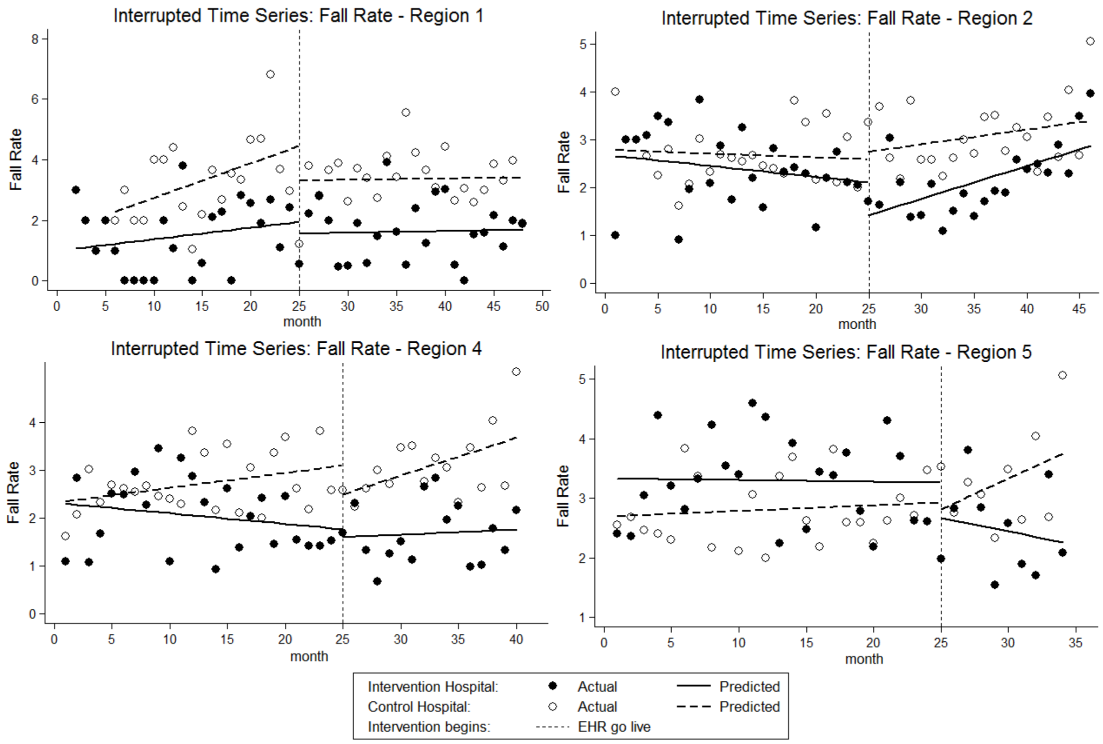

Figure 5S.31. Falls rate in hospital settings before and after EHR go live

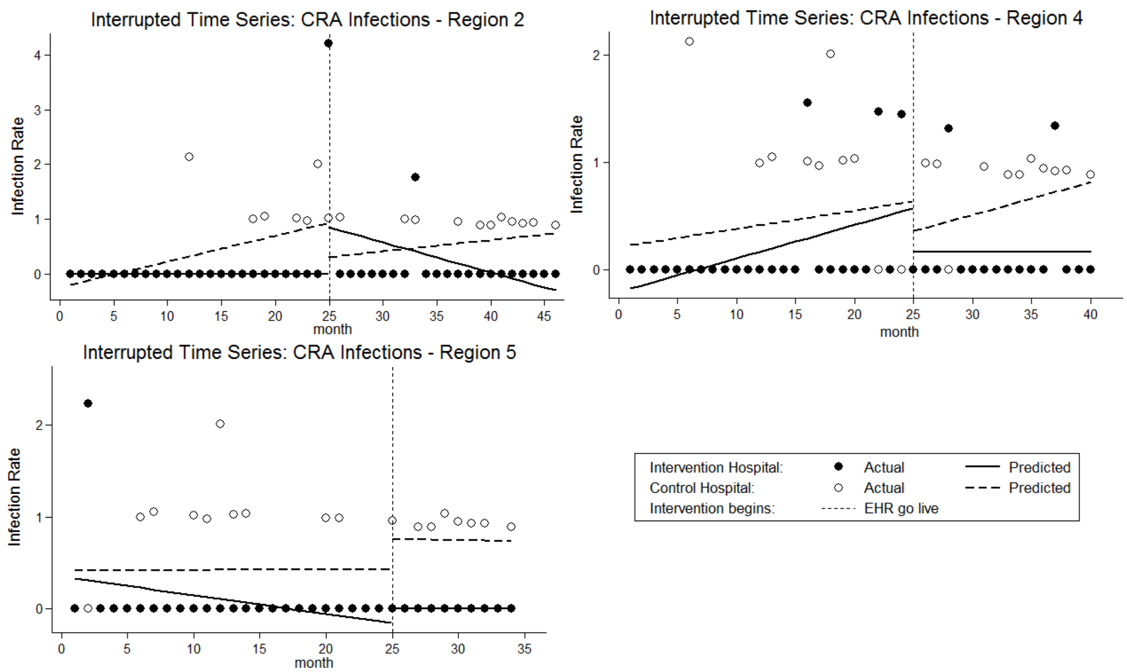

Figure 5S.32. Hospital-acquired CRA infection rate before and after EHR go live

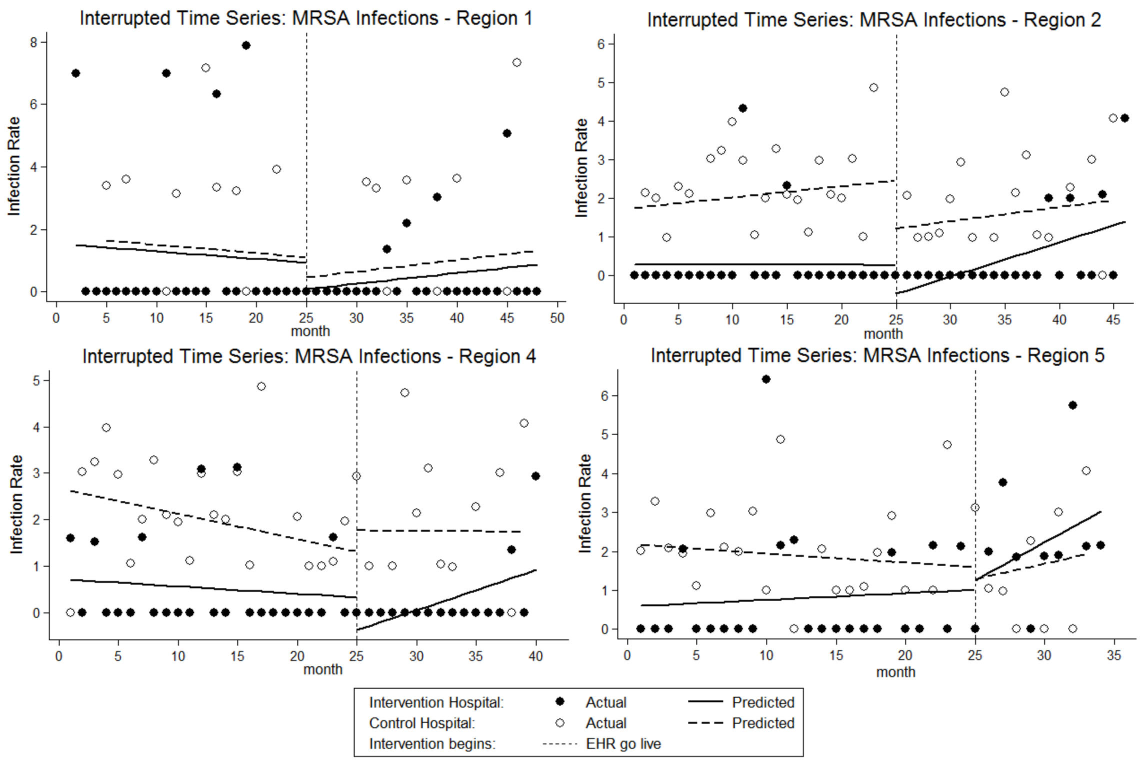

Figure 5S.33. Hospital-acquired MRSA infection rate before and after EHR go live

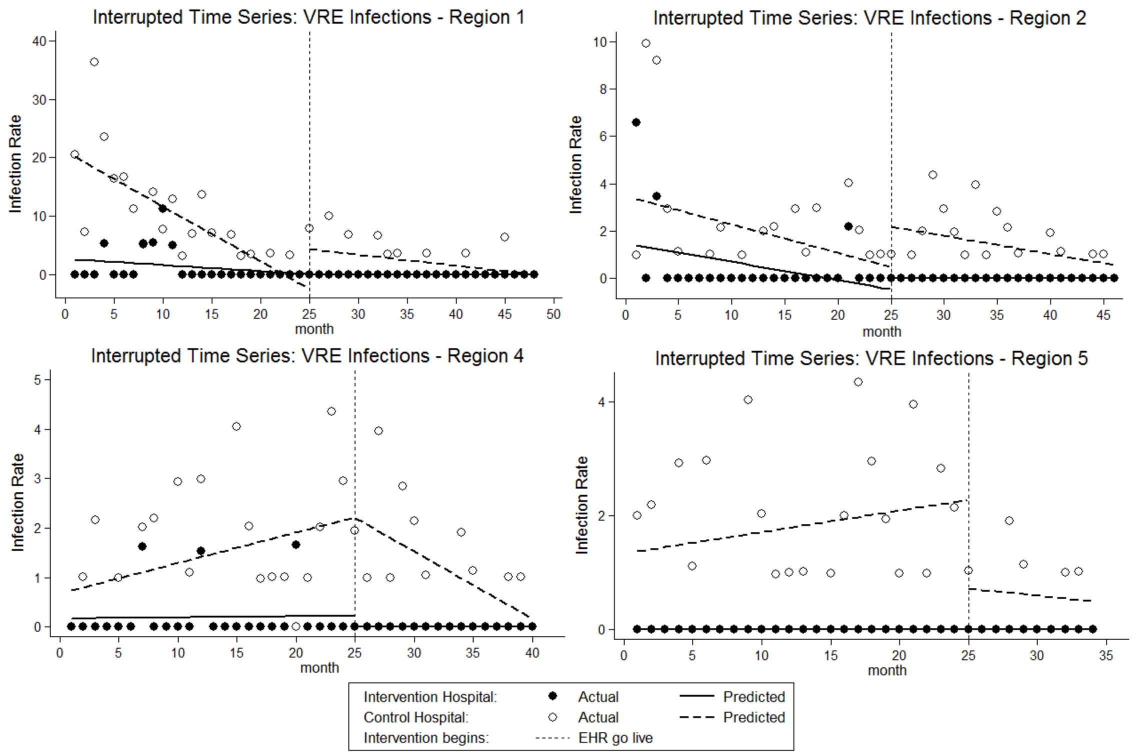

Figure 5S.34. Hospital-acquired VRE infection rate before and after EHR go live

Figure 5S.35. Urinary tract infection rate in hospital settings before and after EHR go live

CHAPTER 6

LOOKING BEHIND THE CURTAIN: IDENTIFYING FACTORS IMPACTING QUALITY, PRODUCTIVITY, AND SAFETY OUTCOMES DURING A LARGE COMMERCIAL EHR IMPLEMENTATION

Tiago K. Colicchio, Damian Borbolla, Vanessa D. Colicchio, Debra L. Scammon, Guilherme Del Fiol, , Watson A. Bowes III, Julio C. Facelli, Scott P. Narus *(Submitted to Health Affairs)*

6.1 Abstract

Guided by a previous longitudinal evaluation of a large commercial electronic health record implementation, we invited clinical employees from the same implementation for semistructured, in-depth interviews to identify factors contributing to performance changes detected on the outcomes previously monitored. Fourteen interviews were recorded and transcribed. Three authors independently coded interview narratives and via consensus produced a final version of 14 factors that potentially affected 15 outcomes of quality, productivity, and safety. Our findings demonstrate that several factors may affect outcomes in different ways during a commercial EHR implementation. This is the first study to explore factors contributing to changes on care outcomes during an information technology (IT) intervention in the health care industry guided by a previous longitudinal

analysis. We recommend continuous identification and monitoring of these factors in future similar evaluations to hopefully increase our understanding of the full impact of health IT interventions.

6.2 Background and Significance

Electronic Health Record (EHR) systems adoption in the U.S. has increased to rates never observed before [1]. As a result, the literature evaluating the impact of health information technology (health IT) interventions on quality, productivity, and safety outcomes has also increased [2]. Several systematic reviews have analyzed health IT evaluations. Overall, these reviews found weak evidence and mixed results across studies, leaving unanswered questions as to the impact of health IT interventions [2-5]. The lack of consistent evidence has been attributed primarily to insufficient descriptions of study settings and interventions; the use of a narrow set of study-specific measurements; and weak research designs that do not consider the longitudinal effects introduced by health IT interventions [2]. Studies from other service sectors such as retail, transportation, and finance, demonstrate that IT adoptions tend to produce positive outcomes only when accompanied by complementary changes or investments (e.g., proper training, upgrading IT infrastructure, adapting workflows) necessary to take full advantage of new technologies [6]. Such factors have not been explored in evaluations of IT adoption in the health care industry and deserve further attention from the broader medical and informatics communities [7].

We have developed a systematic methodology to detect near real-time performance changes during EHR implementations using a large set of measures identified in the literature [8] and suggested by subject-matter experts [9]. In a previous study, our method was tested in a large commercial EHR implementation involving 4 medium-size hospitals and 39 clinics from a large care delivery system [10]. While our methodology was able to effectively detect what and to what extent changes happened, it was not designed to elucidate the dynamics surrounding how they happened. The objective of the present study is to identify factors that may have contributed to changes detected on quality, productivity, and safety outcomes during a large commercial EHR implementation in order to increase our understanding of the full impact of health IT interventions and to guide future research. To elicit those factors, we augmented our quantitative findings with semistructured, in-depth interviews with clinical leaders and staff from 1 medium-size hospital and 10 clinics from the larger implementation previously monitored.

6.3 Materials and Methods

6.3.1 Description of the Previous Longitudinal Evaluation

Intermountain Healthcare, a not-for-profit, integrated care delivery system of 22 hospitals and over 185 clinics covering Utah and southern Idaho, is midway through a project to replace a group of homegrown legacy systems [11-12] with the commercial Millennium EHR (Cerner Corporation, Kansas City, MO, U.S.). The Cerner EHR implementation uses a phased approach with the introduction of the new EHR across 10 geographical regions at different points in time. The implementation in each region followed a “big bang” strategy, replacing all legacy systems at once within that region. We have conducted a longitudinal evaluation of the implementation in the first 5 regions using an interrupted time-series design with parallel control sites [10]. We collected monthly data from February 2013 to July 2017 for 41 outcomes (11 quality measures, 20 productivity measures, and 10 safety measures), selected from an inventory of outcomes likely impacted by health IT interventions [9]. Data were analyzed using an ordinary least squares model [13] that assessed whether the outcomes monitored were impacted immediately after the introduction of the implementation (i.e., EHR "go live") and compared the average change per month in the outcome before and after the go live. Table 6.1 lists the outcomes from our previous evaluation that were subjects of further investigation in the present study.

6.3.2 Design and Settings

We conducted a mixed-methods study with a sequential explanatory design [14]. The design combines interpretation of the quantitative results of our previous study [10] with in in-depth, semistructured interviews with clinical leaders and staff from 1 hospital (375 beds) and 10 primary care clinics from one of the most recent implementation regions (fourth region [10]) to prevent recall bias and at the same time give enough time for participants to be exposed to the new system. The third region did not have any hospitals fitting the inclusion criteria and the fifth region was using the new system for less than 1 year, and its clinicians may not have had enough time to experience all ongoing effects introduced during the implementation. Intermountain Healthcare Institutional Review Board approved the study.

6.3.3 Procedure

We selected all outcomes from the previous quantitative study that detected a statistically significant change after the go live in the targeted settings [10] (Table 6.1), and invited clinical leaders from the departments that represent these outcomes to participate in an in-depth, semistructured interview. The goal of the interview process was to identify factors that may have contributed to changes detected on the outcomes in question. We designed and piloted an interview script to facilitate identification of factors experienced during the new EHR implementation that could have contributed to the changes detected by our previous study. Interview questions can be found in Table 6S.1 in the Supplement. Interviews were conducted in person and lasted from 30 to 60 minutes. Figure 6.1 illustrates an example of the data presented to interviewees to help guide the discussion. Graphs of all measures included in the interviews can be found in Figures 6S.1 to 6S.15 in the Supplement. The interviews were divided into 3 steps: (1) presentation of outcomes; (2) open-ended questions; and (3) referral to other interviewees. In the first step, we provided a brief explanation of the overall objective of the interview to make sure that all informants conceptualize “factors” in the same way (i.e., changes to processes, procedures, assets, or resources that could have affected the outcomes discussed and potentially explain the impacts detected). Interviews were conducted until we had interviewed at least 2 employees for each measure and/or had no more referrals.

6.3.4 Data Analysis

We conducted a systematic content analysis of the interview narratives based on guidelines of Srnka et al. for analyzing qualitative data to derive new theory [15]. The analysis was conducted in 6 stages:

Stages 1 and 2: R*ecording and transcription.* The audio recordings from the interviews were transcribed and deidentified.

Stage 3: Unitization. Transcriptions were split into units that represent informants' responses about each outcome discussed.

Stage 4: *Coding of contributing factors*. Three authors (TKC, DB, VDC) with distinct backgrounds (business, medicine, nursing) independently coded relevant responses that explain potential causes of the changes on each outcome. We initially attempted to use a combined deductive-inductive approach as suggested by Srnka et al.[15], with the sociotechnical dimensions of health IT impact proposed by Sittig and Singh[16], but found that they did not provide enough granularity and depth of the potential causes reported by the informants. We then adopted an inductive approach with each coding author independently identifying categories that explain the changes for each outcome. Multiple sessions were conducted. In each session, the authors collaboratively reviewed initial codes and merged them into a redefined category through consensus. The resulting codes were used in the subsequent iterations. Once all transcripts were coded, similar categories were merged based on consensus, and precise definitions were given to each category, resulting in a final list of factors that may have contributed to the changes on each outcome.

Stage 5: *Coding of covariates*. Once potential causes were identified, informants were asked to suggest data available in electronic format to quantitatively measure their impact on the outcomes in future similar evaluations. The same steps in Stage 4 were followed for the identification of these covariates.

Stage 6: *Identification of factors associated with the new EHR implementation*. Once factors were identified using the coding scheme developed in Stage 4, the three coding authors had a final session to collaboratively reach consensus about the classification of the factors according to the following categories: EHR implementation-associated, partially associated, and not associated.

We used the software package Atlas.ti V.8.0 to facilitate coding of the investigation narratives.

6.4 Results

We interviewed 14 clinical leaders and staff who reported 14 factors that may have contributed to the changes detected on the outcomes. A description of each factor is given below according to the following categories: EHR implementation-associated, partially associated, and not associated. We identified 17 covariates with data available in electronic format to quantitatively measure 12 of the 14 factors identified. Table 6.2 lists contributing factors and the outcomes potentially affected. Table 6.3 lists the covariates. Participants' characteristics can be found in Table 6S.2 in the Supplement.

6.4.1 Factors Associated with the EHR Implementation

Nine factors closely associated with the EHR implementation were reported by informants.

6.4.1.1 Decrease in Communication

Emergency department (ED) leaders reported that due to the increased electronic documentation, communication between nurses and physicians decreased potentially impacting length of stay (LOS) and wait time: “Communication decreased while interruption increased, massively. Our doctors were hiding in the physician lounge.” No specific covariate was identified for monitoring this factor.

6.4.1.2 Incomplete Data Migration

A primary care provider reported that due to a partial data migration from the legacy to the new EHR, some clinical decision support (CDS) alerts were inaccurate, potentially affecting laboratory orders: “I see a lot of overdue stuff. I don’t know if it’s overdue, so it doesn't get ordered.” Acceptance rate of CDS alerts could be a covariate potentially affecting laboratory orders.

6.4.1.3 Increase in Staff

Primary care providers hired new personnel to help with electronic documentation in order to recover to normal volume of patient visits: “Some physicians employed scribes.” ED leaders increased their nursing staff to prevent problems in LOS and wait time: “We hired 12 more nurses over the preceding months.” No specific covariate was identified for monitoring this factor.

6.4.1.4 Learning Curve

The need to allow time to learn the new system hampered clinicians' efficiency in the ED potentially contributing to longer stays and wait time, as reported by an ED manager: "Nurses became efficient with their [legacy] program with time, so you have to give people time." Primary care providers also reported that their practices were less efficient, which may have affected their volume of patient visits: "The issue is people are learning how to use the system. It's not only the physician. It's also the front desk and nursing staff." According to informants, appropriate training resources were available; however, they felt that they only learned the new system in production, and that they needed more support from "technology champions": "Those resources have been deployed to help with go lives in other regions." The number of people allocated for go live support can be a covariate and/or a moderator since it may hamper clinicians' efficiency after the go live, potentially contributing to longer LOS and wait time, and lower volume of visits.

6.4.1.5 Missing Functionality

A primary care provider reported that the new EHR missed a key functionality available in the legacy system that was used in situations where blood pressure was temporarily high, but did not demand treatment changes: "I don't have clinical judgement. Now it's just the number so if they [nurses] don't do a blood pressure clinically perfect it's going to be high." The informant suggested monitoring documentation of acute illness and changes to hypertension treatment as covariates for blood pressure control.

6.4.1.6 Redistribution of Staff or Work

Primary care staff started to orient patients to arrive earlier as an attempt to recover to normal levels of patient visits, as reported by a primary care provider: “We call them and say, ‘You need to make sure you are 10 or 15 minutes before your appointment’.” An infectious disease specialist reported that the new EHR more effectively captured potential infection cases as compared to the legacy system, causing a redistribution of preventive tasks in order to investigate an increased volume of potential surgical site infections (SSIs): “We had to send out other tasks.” ED managers reported that a difference of clinician-patient ratio between nursing and physician staffs was the most significant factor contributing to longer LOS and wait time: “They [physicians] didn’t change their patient ratios even though they were massively increasing their workload.” ED Informants suggested monitoring provider-patient ratio as a covariate potentially affecting LOS and wait time.

6.4.1.7 Resistance to Learn or Use a New EHR

Intensive care unit (ICU) nurses reported multiple examples of colleagues who demonstrated a resistance to learn and use the new EHR, which potentially affected employee turnover: “They said, ‘the day the system goes live, I quit’.” This resistance was perceived as more likely to affect older employees: “It seemed to be harder on older people.” Management tried to implement diverse training strategies, but were still unsuccessful, as reported by an ICU manager: “They didn't want to learn a new system.” Informants suggested tracking employee age as a covariate potentially affecting employee turnover.

6.4.1.8 System Configuration

System configuration includes functionality that was added or modified during the implementation and affected multiple outcomes such as laboratory orders, time documenting after hours, and infections. A primary care provider reported that CDS alerts were progressively added to the system to decrease inappropriate laboratory orders: “We actually would have alerts saying, ‘Why are you ordering this, it looks like it’s not necessary’.” Another primary care provider reported that he frequently completed documentation after hours remotely: “What about the mobile app? Last night I couldn't sleep so I did labs from like 1:00 to 2:00 am.” Infectious disease specialists reported that the new EHR captured more potential SSI cases than they could investigate: “There were just so many we finally said, ‘Hey, we're going to look at every patient in the hospital’.” This functionality improved over time and may have contributed to the identification of more infections associated with hysterectomy and colon surgeries. They also reported that the new system was configured to trigger automatic orders to isolate patients every time a suspected or historical infection was documented which increased the number of patients in isolation: “MRSA and CDiff are going down, which makes sense with isolation increasing.” Primary care informants suggested monitoring acceptance rate of CDS alerts as a covariate potentially affecting laboratory orders. Infectious disease specialists suggested monitoring the number of patients in isolation as a covariate affecting MRSA and CDiff infections, and the number of potential infections captured by the EHR as a covariate for SSIs.

6.4.1.9 Workflow Redesign

Workflow changes affected multiple outcomes in both types of settings. Two primary care providers reported that they were not able to recheck blood pressure in some cases, which potentially affected blood pressure control: “Because the log-in process was so painful, people were not rechecking blood pressures at the time.” Due to the implementation of computerized provider order entry (CPOE), nursing staff had to wait for physicians to enter laboratory orders before collecting laboratory samples, which may have decreased the number of laboratory orders: “Now they [nurses] need us [physicians] to sign off before it gets done.” A primary care director reported that providers were oriented to document as much as possible at the time of the visit to avoid after hours documentation: “We talked to the physicians to get the documentation done at the time of the visit.” However, in most cases physicians were not able to follow the orientation, as reported by a primary care provider: “On Tuesday, I stop seeing patients at 11:30 and chart the ones from Monday until 5 o’clock.” ED leaders implemented changes in patient flow to decrease LOS and wait time: “Part of that [recovery] is interventions we did addressing patient flow.” Primary care informants reported that increased volume of visits may increase documentation and suggested monitoring patient visits as a covariate for time documenting after hours.

6.4.2 Factors Partially Associated with the EHR Implementation

Two factors partially associated with the EHR implementation were reported by informants.

6.4.2.1 Change in Care Pathways

Change in care pathways potentially affected the rate of readmissions for heart failure (HF) patients, as reported by a cardiovascular director: “Our team was updating our protocols to improve these data; we have [order sets] for admissions.” Informants suggested monitoring appropriate use of medication for heart failure as a covariate for readmission rate.

6.4.2.2 Intentional Decrease in Volume of Work

A primary care director reported that primary care providers were oriented to limit their schedules after the go live: “Clinics had their schedules limited in a way that would allow us to have time to deal with the new system.” This orientation may have affected patient visits and laboratory orders, as reported by a primary care provider: “You have a drop in volume, so labs would probably go down.” Informants suggested monitoring the number of patient visits as a covariate for laboratory orders.

6.4.3 Factors not Associated with the EHR Implementation

Three factors not associated with the EHR implementation were reported by informants.

6.4.3.1 Health Insurance Changes

Changes to health insurance coverage affected all primary care outcomes with the exception of blood pressure control. Primary care providers reported that new requirements for coding procedures increased time documenting after hours: “We didn’t have a focus on trying to capture every single diagnosis for Medicare before." One primary care provider reported that insurance companies progressively removed coverage of tests ordered in physical examinations: "The insurance change was a push back on physicians to kind of change our behavior," which potentially caused a decrease in laboratory orders. He also reported that patients are more frequently opting for health savings accounts; such patients tend to avoid chronic disease management visits, which impacts compliance to diabetes bundle and patient visits: "People don't come frequently for their diabetes control because it's out of their pocket." Another primary care provider reported that their top health insurance lost a big contract close to the go live, which may have decreased the number of new patient visits: "A contract with [company name hidden] was supposed to come to us but it went to [company name hidden]." Informants suggested monitoring risk adjustment factor as a covariate for time documenting after hours; type of health insurance as a covariate for diabetes bundle and patient visits; rate of laboratory tests covered for physical exams as a covariate for laboratory orders; and rate of patients per top health insurance as a covariate for new patient visits.

6.4.3.2 Patient Engagement

According to one primary care provider, two diabetes bundle items, hemoglobin A1c and eye exam, depend on patient engagement: "They [patients] have to go to an ophthalmologist." He also reported: "He [patient] is working in two jobs, eating out constantly, so his A1c is 11 now." The provider suggested monitoring each bundle item in isolation.

6.4.3.3 Seasonal Pattern

The implementation happened in a period of increased ED visits: "This is seasonal… it wasn't related to the new EHR." The increased visits may have affected LOS and wait time: "The volume itself will affect the length of stay and the door to provider." ED leaders suggested monitoring the number of ED visits as a covariate for LOS and wait time.

6.5 Discussion

To the best of our knowledge, this is the first study to investigate factors contributing to changes on quality, productivity, and safety outcomes during a health IT intervention guided by the results of a longitudinal evaluation. Our focus on the understanding of time-sensitive effects observed during a large EHR implementation allowed identification of diverse factors potentially affecting the outcomes. The diversity of factors identified indicates the need for adapting processes, procedures, and resources in order to take full advantage of new technologies is as important for the health care sector as it is for other services sectors. Our findings lend support to the need for more robust evaluations that consider the impact of these factors.

Hospital outcomes were more consistently affected by factors associated with the new EHR implementation. Several factors affected ED outcomes; however, our qualitative analysis revealed that the lack of go live support intensified and expanded clinicians' learning curve, and may have been the most plausible explanation for longer stays and wait time. Although the nursing staff decreased their patient ratios for several weeks, the ED as a department was less efficient because ED physicians were not using an electronic ordering functionality in the legacy EHR, and faced a significant change moving from paper-based ordering to electronic ordering. The lack of go live support affected this process for several weeks. Most informants reported that appropriate training resources were available, but perceived that effective learning seems to happen only from the use of the new system in the operational environment, and felt that they needed additional support from "technology champions." This learning curve could have been controlled with proper planning of go live support and anticipation of human-computer interface problems. Although employee turnover has been rated by subject-matter experts as the least relevant measure for assessing EHR implementations [9], our findings indicate that some employees may resist learning and using a new EHR and potentially quit their jobs or advance their retirement. Such resistance could have been anticipated with the use of validated instruments for measuring acceptance of new technologies [18]. Surgical site infections increased after the go live mostly due to the EHR's increased rate of detection of potential infection cases to investigate; however, this increase in detection was observed only after the functionality was improved, which was not anticipated and happened while the system was already operational. MRSA and CDiff infections may have decreased likely due to a system configuration that prospectively increased the number of patients in isolation by requiring providers to complete isolation orders generated automatically. Primary care informants indicated that a key functionality was not available in the new EHR and felt that they lost clinical judgement to decide when patients were hypertensive. Identification of missing functionality could have been controlled by stakeholders with enhanced involvement of end-users in the design and customization of the new EHR, as recommended by experts in the field [19], but frequently ignored in similar interventions [20].

Ambulatory outcomes were more consistently affected by factors not associated with the new EHR implementation, except for a seasonal pattern that potentially affected ED measures. The constant changes to insurance coverage and billing documentation may have decreased the volume of patient visits and laboratory orders, and, in spite of that, added an enormous documentation burden. Such a burden was worsened by the new EHR implementation due to the time necessary to learn the new system. In our previous study, time documenting after hours in the new EHR ranged from 0.8 to 2.3 hours per provider per month [10]. The same outcome has been reported elsewhere as 1.4 hours per provider per weekday [21]. Our qualitative analysis found that providers frequently blocked periods of their schedule in order to document previous visits during work hours, such a documentation was not captured as “after hours” by our measurements, which may explain the smaller times observed in our institution. Although insurance changes are not controlled by stakeholders, early involvement of end-users and allocation of “technology champions” for go live support are processes that can be internally controlled and could have mitigated the documentation burden. Providers suggested that a decrease in compliance with the diabetes bundle is more likely to have been affected by a decrease in chronic disease management visits, which is a factor out of their control. We identified data available in electronic format to quantitatively monitor 17 covariates in future evaluations in order to confirm or discard the hypothesis that the factors identified can contribute to performance changes on care outcomes.

6.5.1 Implications for Future Research and EHR Implementations

We recommend more attention to preventive actions such as allocation of "technology champions" after the go live, for as long as needed, especially in time-constrained settings such as the ED. Another strategy is to simulate the workflow in the production environment as demonstrated elsewhere [21]. Health care leaders must try to anticipate that some employees might resist learning the new EHR and develop strategies to engage these employees as early as possible. Involvement of end-users in the early stages of system customization is also paramount. Finally, we recommend a mixed-method approach in future evaluations including a qualitative analysis guided by longitudinal quantitative evaluations using our previously tested methodology [9-10] and monitoring of covariates. Such an approach is necessary to improve the capacity of health care leaders, health IT vendors, and researchers to more effectively monitor EHR implementations and hopefully increase the understanding of the full impact of health IT interventions.

6.5.2 Limitations

Information obtained in the interviews was susceptible to the personal biases of each informant. We were able to interview only 14 informants from only one implementation region, which may have compromised identification of other factors. Nonetheless, we interviewed at least 2 employees per measure, and in some cases the only employees specialized in the outcomes in question (e.g., the only 2 infectious disease specialists), which may have led to the identification of the most prominent factors. Intermountain Healthcare has extensive informatics experience and the perceptions of its employees may differ from other institutions. We were not able to identify covariates for 2 factors reported.

6.6 Conclusion

We conducted a mixed-methods study combining quantitative results of a longitudinal evaluation of a commercial EHR implementation with semistructured, in-depth interviews and identified 14 factors contributing to changes on care outcomes. We also identified 17 covariates for monitoring 12 of these factors. Our findings demonstrate that several factors may affect outcomes in different ways during a commercial EHR implementation and lend support for more robust evaluations that consider the impact of these factors to hopefully increase our understanding of the impact of health IT interventions.

6.6.1 Acknowledgements

We thank the leaders and clinicians from Intermountain Healthcare who participated in the interviews. The authors acknowledge Intermountain Healthcare, Salt Lake City, UT, USA for funding this study. JCF has been partially supported by the National Center for Advancing Translational Sciences under Award Number 5UL1TR001067-03.

6.7 References

[1] Adoption of electronic health record systems among U.S. non-federal acute care hospitals: 2008-2015 [Internet]. [cited 2017 October 10]. Available from: https://dashboard.healthit.gov/evaluations/data-briefs/non-federal-acute-care-hospital-ehr-adoption-2008-2015.php

[2] Jones SS, Rudin RS, Perry T, Shekelle PG. Health information technology: an

updated systematic review with a focus on meaningful use. Ann Intern Med. 2014 Jan 7;160(1):48–54.

[3] Chaudhry B, Wang J, Wu S, Maglione M, Mojica W, Roth E, et al. Systematic review: impact of health information technology on quality, efficiency, and costs of medical care. Ann Intern Med. 2006 May 16;144(10):742–52.

[4] Goldzweig CL, Towfigh A, Maglione M, Shekelle PG. Costs and benefits of health information technology: new trends from the literature. Health Aff. 2009 Mar 1;28(2):w282–93.

[5] Buntin MB, Burke MF, Hoaglin MC, Blumenthal D. The benefits of health information technology: a review of the recent literature shows predominantly positive results. Health Aff. 2011 Mar 1;30(3):464–71.

[6] Brynjolfsson E, Hitt LM. Beyond the productivity paradox. Commun ACM. 1998;41(8):49–55.

[7] Kellermann AL, Jones SS. What it will take to achieve the as-yet-unfulfilled promises of health information technology. Health Aff. 2013 Jan 1;32(1):63–8.

[8] Colicchio TK, Facelli JC, Del Fiol G, Scammon DL, Bowes III WA, Narus SP. Health information technology adoption: understanding research protocols and outcome measurements for IT interventions in health care. J Biomed Inform. 2016 Oct;63:33–44.

[9] Colicchio TK, Fiol GD, Scammon DL, Bowes III WA, Facelli JC, Narus SP. Development and classification of a robust inventory of near real-time outcome measurements for assessing information technology interventions in health care. J Biomed Inform. 2017 Sep;73:62–75.

[10] Colicchio TK, Del Fiol G, Scammon DL, Bowes III WA, Facelli JC, Narus SP. Detecting performance changes on quality, productivity, and safety outcomes during a large commercial electronic health record system implementation. J Am Med Inform Assoc (Submitted).

[11] G.J. Kuperman, R.M. Gardner, T.A. Pryor. HELP: A dynamic hospital information system. Springer, New York. 1991.

[12] Clayton PD, Narus SP, Huff SM, Pryor TA, Haug PJ, et al. Building a comprehensive clinical information system from components the approach at Intermountain Health Care. Methods Inf Med. 2003;42(1):1–7.

[13] Linden A. Conducting interrupted time-series analysis for single- and multiple-group comparisons. Stata J 2015;15(2):480-500.

[14] Ivankova NV, Creswell JW, Stick S. "Using mixed-methods sequential explanatory design: from theory to practice". Field Methods. 2006;18(1):3–20.

[15] Srnka KJ, Koeszegi ST. From words to numbers: how to transform qualitative data into meaningful quantitative results. Schmalenbach Bus Rev. 2007;59:29–57.

[16] Sittig DF, Singh H. A new sociotechnical model for studying health information technology in complex adaptive healthcare systems. Qual Saf Health Care. 2010 Oct 1;19(Suppl 3):i68–74.

[17] Sittig DF, Ash JS, Guappone KP, Campbell EM, Dykstra RH. Assessing the anticipated consequences of computer-based provider order entry at three community hospitals using an open-ended, semi-structured survey instrument. Int J Med Inform. 2008 Jul;77(7):440–7.

[18] Venkatesh V, Morris MG, Davis GB, Davis FD. User acceptance of information technology: toward a unified view. MIS Quarterly. 2003 Sep 1;27(3):425–78.

[19] Ash JS, Berg M, Coiera E. Some unintended consequences of information technology in health care: the nature of patient care information system-related errors. J Am Med Inform Assoc. 2004;11(2):104–12.

[20] Arndt BG, Beasley JW, Watkinson MD, Temte JL, Tuan W-J, Sinsky CA, et al. Tethered to the EHR: primary care physician workload assessment using EHR event log data and time-motion observations. Ann Fam Med. 2017 Sep 1;15(5):419–26.

[21] Wright A, Aaron S, Sittig DF. Testing electronic health records in the "production" environment: an essential step in the journey to a safe and effective health care system. J Am Med Inform Assoc. 2017 Jan 1;24(1):188–92.

Table 6.1 Outcome measures from the longitudinal study included in the qualitative analysis.

Type of measurement	**Measure**	**Description**	**Significant impact observed in the previous evaluation**
Primary care Quality measures	Blood pressure control	Rate of diabetes patients with blood pressure in control	Decreased immediately after the go live followed by an increase per month
	Diabetes Bundle	Composite measure for diabetes control	Decreased immediately after the go live and continued to decrease per month
Primary care Productivity measures	Laboratory orders	Number of orders of laboratory tests	Decreased immediately after the go live
	New patient visits	Rate of new patient visits to ambulatory settings	Decreased immediately after the go live
	Patient visits	Number of patient visits to ambulatory settings	Decreased immediately after the go live followed by an increase per month
	Time documenting after hours	Time spent by provider documenting in electronic health records after 6 p.m.	Increased per month after the go live
Hospital Quality measure	Readmission rate	Rate of heart failure patients readmitted within 30 days	Decreased immediately after the go live
Hospital Productivity measures	ED LOS	Length of stay of patients in the emergency department	Increased immediately after the go live followed by a decrease per month
	ED visits	Number of patient visits to the emergency department	Decreased immediately after the go live
	ED wait time	Mean time between patient arrival and seen by provider in the emergency department	Increased immediately after the go live followed by a decrease per month
	Employee turnover	Rate of employee contracts terminated	Increased immediately after the go live
Hospital Safety measures	Abdominal hysterectomy infection rate	Rate of hospital-acquired surgical site infections for abdominal hysterectomy surgeries	Increased per month after the go live
	Colon surgery infection rate	Rate of hospital-acquired surgical site infections for colon surgeries	Increased per month after the go live

Table 6.1. Continued

Type of measurement	Measure	Description	Significant impact observed in the previous evaluation
Hospital Safety measures	Hospital-acquired CDiff infection rate	Rate of hospital-acquired infections of Clostridium Difficile	Decreased per month after the go live
	Hospital-acquired infection MRSA rate	Rate of hospital-acquired infections of Methicillin-resistant Staphylococcus aureus	Decreased immediately after the go live

Table 6.2 Explanatory factors that potentially affected the outcomes.

Contributing factor	**Implementation-associated**	**Outcome(s) impacted**	**Examples**
Decrease in communication	Yes	ED LOS ED wait time	Due to CPOE adoption communication between providers decreased and interruptions increased
Incomplete data migration	Yes	Laboratory orders	Partial data were migrated from the legacy system to the new EHR comprising accuracy of overdue test alerts
Increase in staff	Yes	ED LOS ED wait time Patient visits	Twelve ED nurses were hired prior to the go live Some PC physicians employed scribes
Learning curve	Yes	ED LOS ED wait time Patient visits New patient visits	Due to new functionality to learn, recovery to baseline levels took longer than expected
Missing functionality	Yes	Blood pressure	The new EHR missed a key functionality that allowed overlapping of BP measurement
Redistribution of staff or work	Yes	ED LOS ED wait time Patient visits New patient visits Abdominal hysterectomy Colon surgery	ED Physicians decreased their patient ratios for three days only Patients were oriented to arrive earlier for their PC visits Some preventive tasks were redistributed among infection team members
Resistance to learning or using a new HER	Yes	Employee turnover	Some clinical personnel quit to avoid learning or using a new EHR In some cases they anticipated their retirement
System configuration	Yes	Laboratory orders Time documenting after hours Abdominal hysterectomy Colon surgery MRSA CDiff	Laboratory alerts were added progressively PC providers used a mobile app to complete visit documentation The new EHR had a more robust capability for capturing potential infections, which was improved over time

Table 6.2. Continued

Contributing factor	**Implementation-associated**	**Outcome(s) impacted**	**Examples**
Workflow redesign	Yes	ED LOS ED wait time Blood pressure control Laboratory orders Time documenting after hours	Patient flow was adapted at the ED Physicians may not have double checked BP in some cases The process for collecting lab samples at the clinics was redesigned due to CPOE adoption
Change in care pathways	Partially	Readmission rate	Care pathways were adapted to improve HF treatment Not all protocols were configured as order sets
Intentional decrease in volume of work	Partially	Patient visits New patient visits Laboratory orders	Physicians were seeing fewer patients in order to complete electronic documentation
Health insurance changes	No	Diabetes bundle Patient visits New patient visits Laboratory orders Time documenting after hours	Patients with health savings accounts tend to avoid chronic disease management visits Insurance companies stopped covering the most common tests in physical exams and started to require more strict coding of procedures
Patient Engagement	No	Diabetes bundle	Half of the bundle items depend mostly on patient engagement on treatment
Seasonal pattern	No	ED visits ED LOS ED wait time	The go live was postponed due to problems in previous regions and happened in a time of a slight pick

Source: Explanatory factors and outcomes impacted by them identified by the authors in the qualitative analysis. Notes: EHR: electronic health records; PC: Primary care; ED: emergency department; LOS: length of stay; CDiff: Clostridium Difficile; MRSA: Methicillin-resistant Staphylococcus aureus.

Table 6.3 Covariates for monitoring factors that may affect outcomes.

Setting	Measure	Confounding variable(s)	Examples
Ambulatory	Blood pressure control	Change in hypertension pharmacotherapy Acute illness	Pharmacotherapy changes may be associated with hypertension status Acute illnesses may cause a temporary hypertension
	Diabetes Bundle	Individual bundle items Type of health insurance	Type of health insurance may be associated with chronic disease management
	Laboratory test orders	CDS alerts accepted Lab tests covered per type of visit Patient visits	Alerts of appropriate lab test may be associated with lab orders Patient visits may be associated with lab orders
	Time documenting in EHR after hours	Risk adjustment factor Patient visits	Risk adjustment factor may be associated with electronic documentation Patient visits may be associated with lab orders Previous visits may be documented during work hours
	Patient visits	Time documenting previous visits Type of health insurance	Increased documentation may decrease patient visits Type of health insurance may decrease patient visits
	New patient visits	Proportion of patients per top insurance providers	Loss of patients from top insurance may decrease the number of new patients
Hospital	ED visits	Not identified during interviews	Not identified during interviews
	ED LOS ED wait time	ED visits Provider-patient ratio Go live support personnel	More ED visits may increase LOS and wait time Provider patient ration may be associated with LOS and wait time More personnel for go live support may increase efficiency
	MRSA infections CDiff infections	Patients in isolation	Number of patients in isolation may decrease infection rate
	Abdominal hysterectomy infections Colon surgery infections	Number of suspected infection cases according to the CDC's NHSN	Number of potential infections captured by the EHR may help increase identification of true cases
	Employee turnover	Employee age	Employee age may be associated with resistance to a new EHR potentially increasing employee turnover
	Readmission rate	Appropriate use of medication for heart failure	Adherence to care pathways for heart failure may be associated with decreased readmission rate

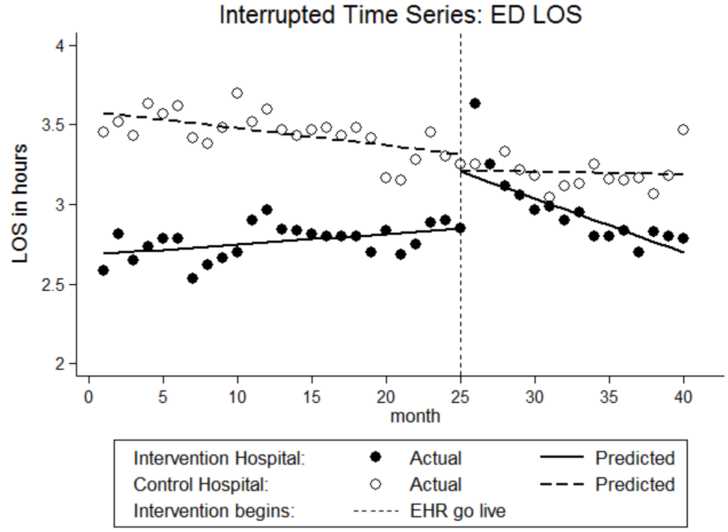

Figure 6.1 Example of data presented in the interviews.
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the median length of stay in hours in the Emergency Department (ED) over time with a significant increase immediately after the go live in the intervention site when compared to the control site. The graph was presented to ED leaders during the interview process.

6.8 Supplementary Materials

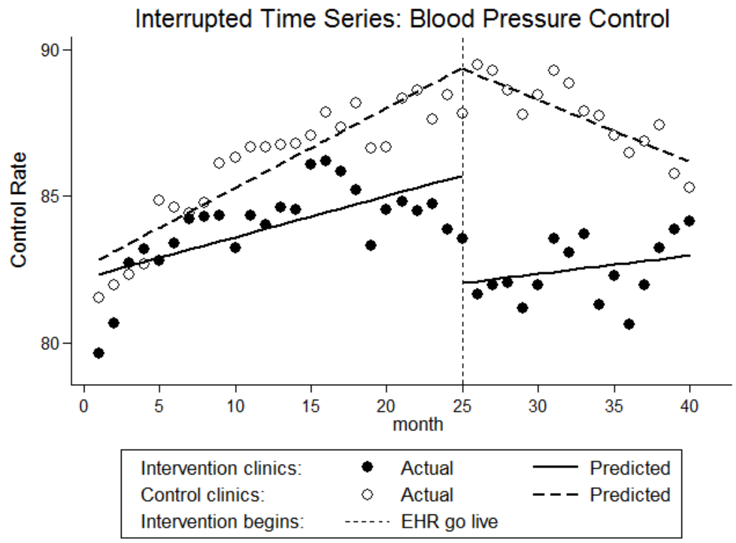

Figure 6S.1. Blood pressure control rate per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the proportion of diabetes patients with blood pressure in control over time with a significant decrease immediately after the go live followed by a significant increase over time in the intervention sites when compared to control sites.

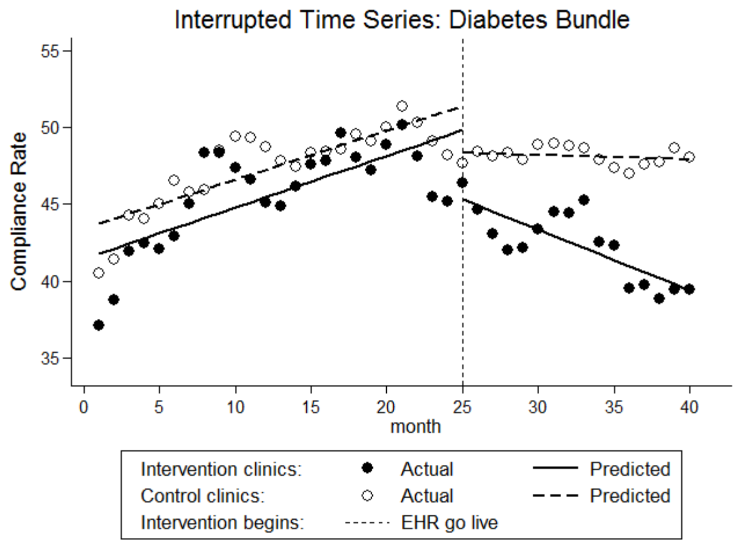

Figure 6S.2. Diabetes bundle compliance per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the proportion of diabetes patients in compliance with all bindle items over time with a significant decrease immediately after the go live and over time in the intervention sites when compared to control sites.

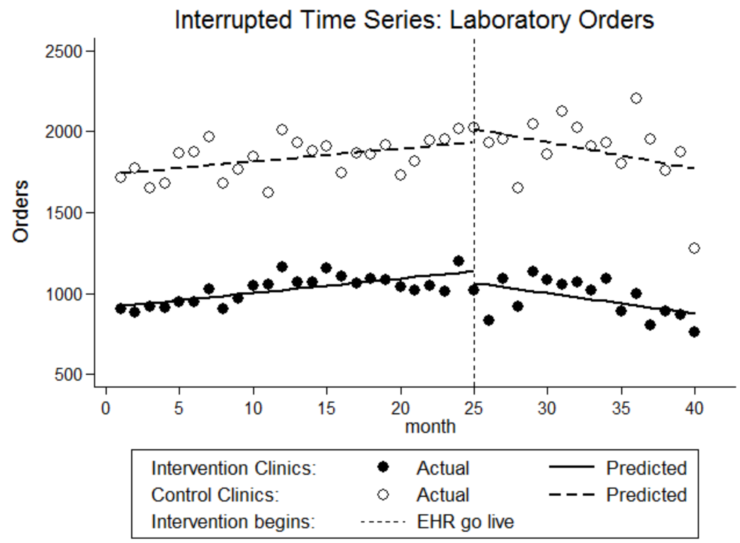

Figure 6S.3. Number of laboratory test orders per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the number of laboratory orders over time with a significant decrease immediately after the go live in the intervention sites when compared to control sites.

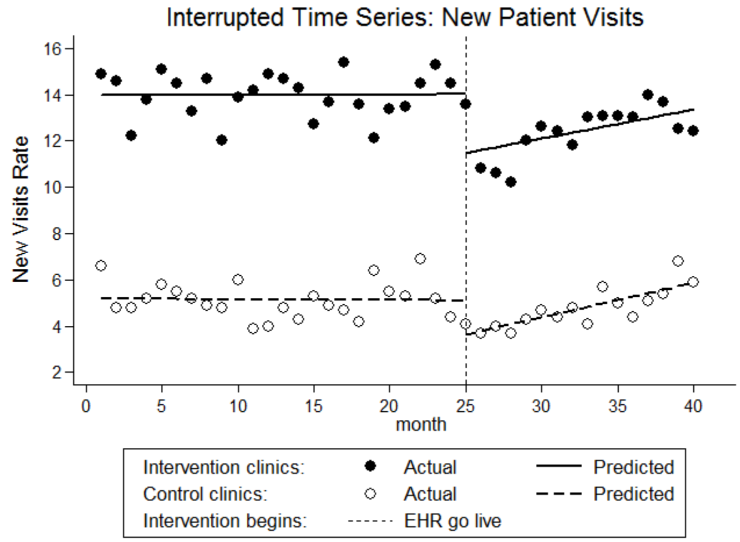

Figure 6S.4. Rate of new patient visits per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the proportion of diabetes patients with blood pressure in control over time with a significant decrease immediately after the go live in the intervention sites when compared to control sites.

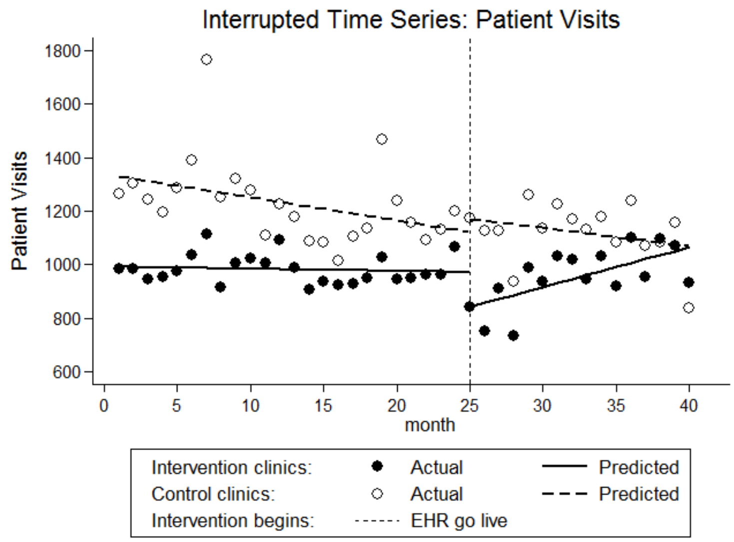

Figure 6S.5. Total patient visits per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the number of patient visits over time with a significant decrease immediately after the go live followed by a significant increase over time in the intervention sites when compared to control sites.

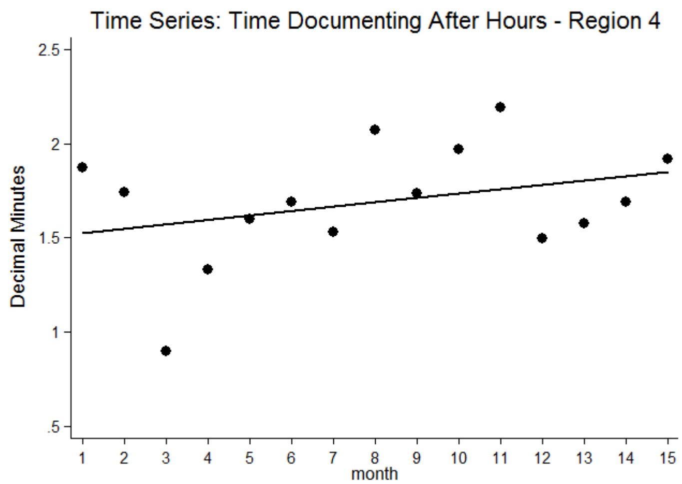

Figure 6S.6. Time documenting in the EHR after 6 p.m. per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates average time documenting per provider per patient after 6 p.m. in the post-intervention period with a significant increase over time in the intervention sites. Data to calculate this measure were available only in the new EHR and were assessed in the intervention without a baseline and control.

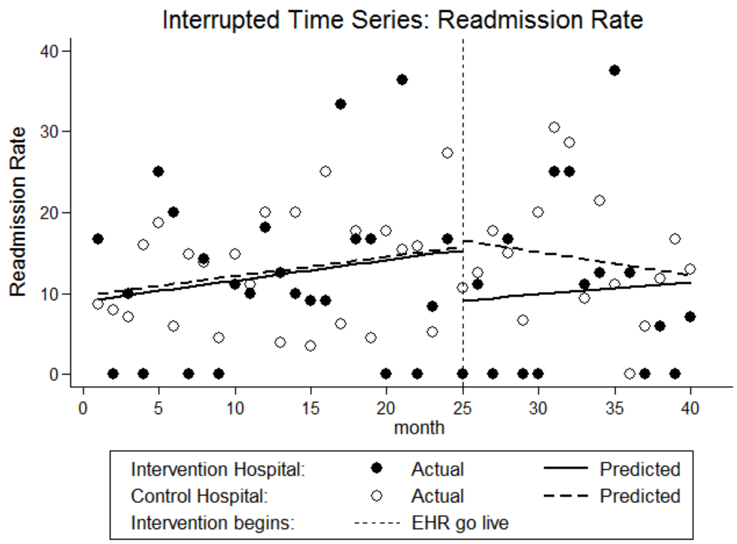

Figure 6S.7. Rate of heart failure patients readmitted within 30 days per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter). Notes: The graph illustrates readmission rate over time with a significant decrease immediately after the go live in the intervention site when compared to the control site.

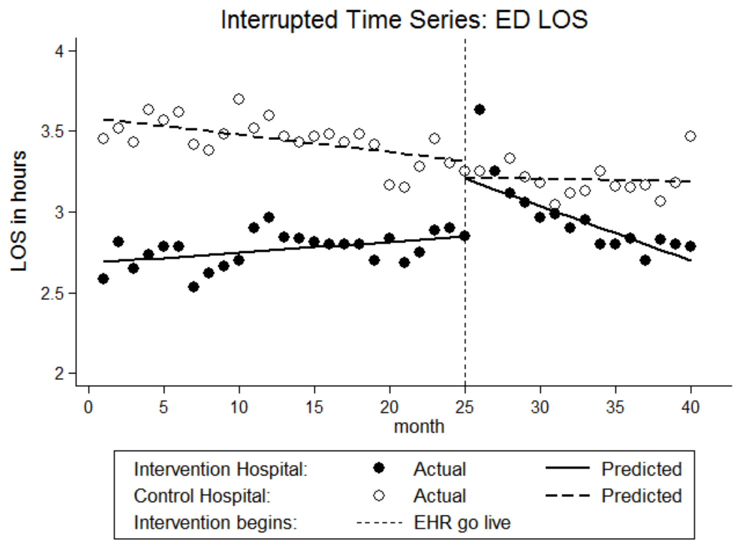

Figure 6S.8. Emergency department length of stay per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the median length of stay in hours in the Emergency Department (ED) over time with a significant increase immediately after the go live followed by a significant decrease over time in the intervention site when compared to the control site.

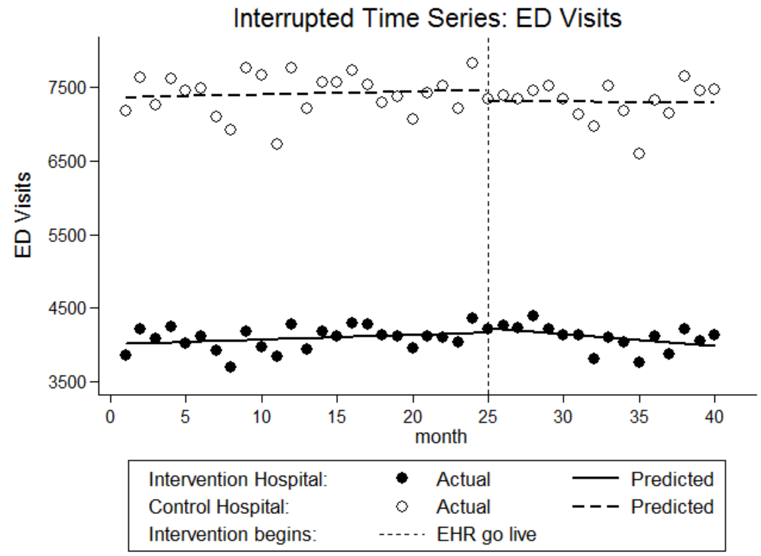

Figure 6S.9. Emergency department visits per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the number ED visits over time with a significant increase immediately after the go live in the intervention site when compared to the control site.

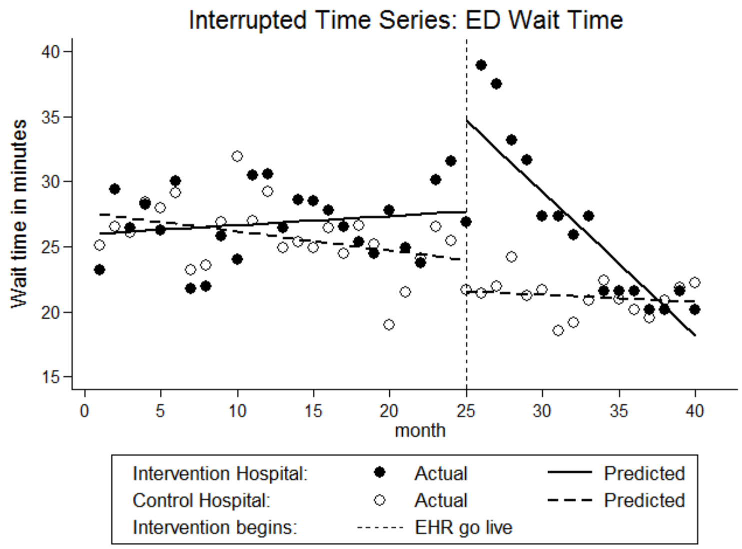

Figure 6S.10. Emergency department wait time per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the median time to be admitted in the ED over time with a significant increase immediately after the go live followed by a significant decrease over time in the intervention site when compared to the control site.

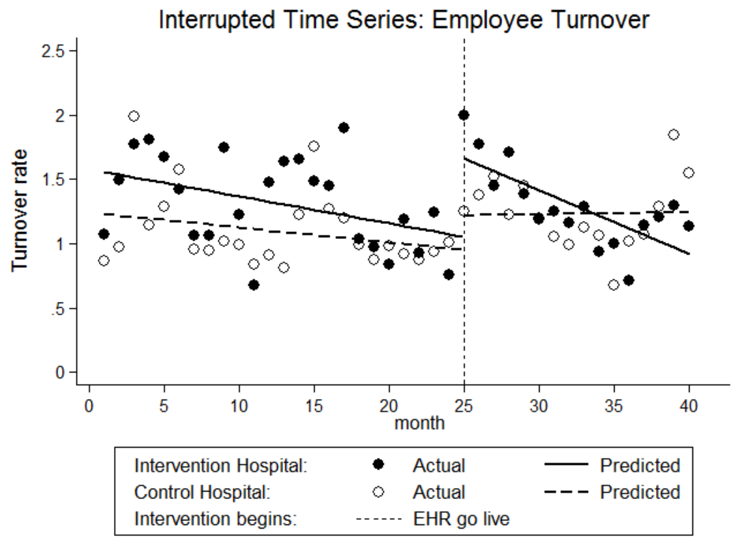

Figure 6S.11. Employee turnover rate per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the employee turnover rate over time with a significant increase immediately after the go live in the intervention site when compared to the control site.

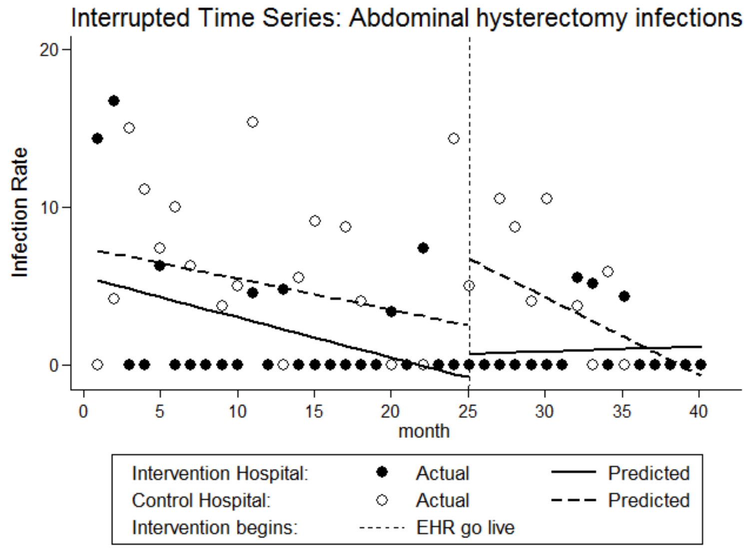

Figure 6S.12. Rate of hospital-acquired abdominal hysterectomy infections per month Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the rate of infections over time with a significant increase per month after the go live in the intervention site when compared to the control site.

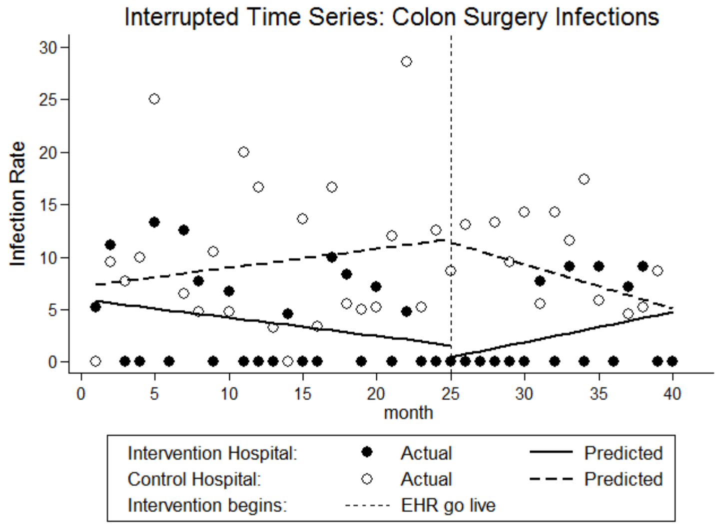

Figure 6S.13. Rate of hospital-acquired colon surgery infections per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the rate of infections over time with a significant increase per month after the go live in the intervention site when compared to the control site.

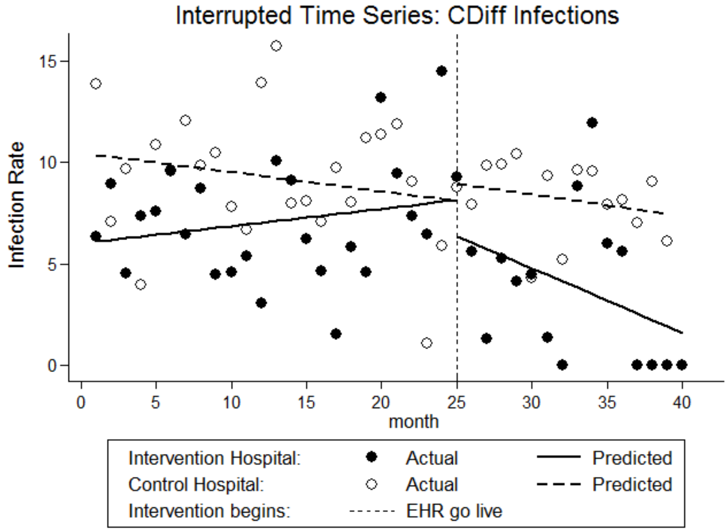

Figure 6S.14. Rate of hospital-acquired infections of Clostridium Difficile per month
Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes:
The graph illustrates the rate of infections over time with a significant decrease per month after the go live in the intervention site when compared to the control site.

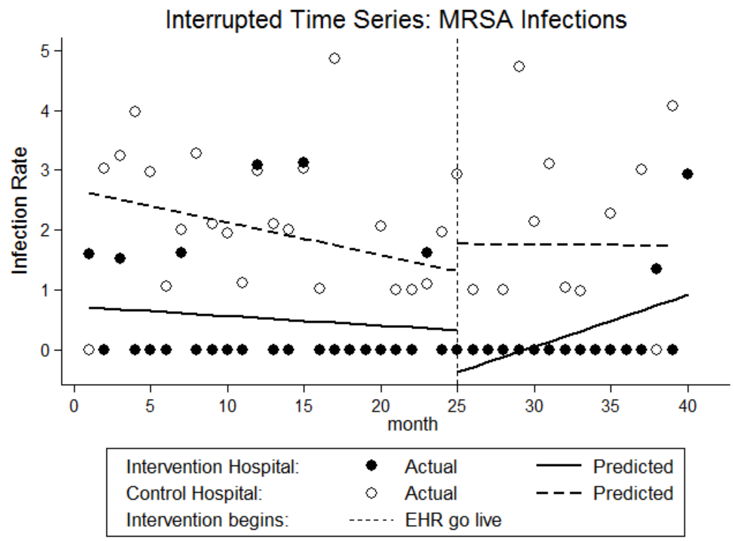

Figure 6S.15. Rate of hospital-acquired infections of Methicillin-resistant Staphylococcus aureus per month

Source: Graph retrieved from our previous longitudinal evaluation (Chapter 5). Notes: The graph illustrates the rate of infections over time with a significant decrease immediately after the go live in the intervention site when compared to the control site.

Table 6S.1. Interview script

Interview phase	Questions asked
Questions about perceptions of the performance changes detected and identification of complementary factors that could have caused those changes	a. During the new EHR go live, did you notice the performance change(s) on the outcomes presented here? b. What other changes to processes, procedures, resources, and assets were introduced during the implementation of the new EHR? c. Do you believe these changes are associated with the outcome(s) here presented? If so, how did the change(s) impact the outcome and your work?
Questions about the time when these factors were introduced	a. Please describe how you were informed about and prepared for the changes previously discussed? b. When these changes were introduced (before, after go live)? c. Are they still impacting your work? How?
Questions to understand how these factors affected the study outcomes	a. Please tell me about any strategies implemented by the IH leadership to mitigate/maximize the impact introduced by the implementation or by the changes previously discussed? b. Were they effective? c. Do you believe that lack of training and/or go live support could have contributed to these changes and impacted the outcomes?
'What-if' queries: questions to identify confounders that could be measured with data available in electronic format in future evaluations to monitor the factors elicited by the interviews	Are there any other process or outcome with data available in electronic format that could be measured as a confounder (potential alternative explanation to the impact observed) for monitoring the changes previously discussed? Other what-if queries were identified during the interviews based on the complementary factors described by interviewee.

Source: Interview script.

Table 6S.2 – Interviewees' characteristics

Intermountain leaders and staff - Semi-structured interviews	
Age, years (SD)	44.2 (11.0)
Female, n (%)	12 (40)
Role, n (%)*	
Director	2 (14.2)
Manager	4 (28.5)
Physician	3 (21.4)
Staff	5 (35.7)
Consultant	1 (7.1)
Department, n (%)	
ICU	5 (35.7)
Primary Care	3 (21.4)
Emergency Department	2 (14.2)
Cardiovascular	2 (14.2)
Infection Prevention	2 (14.2)
Main educational background, n (%)	
Nursing	11 (78.5)
Medicine	3 (21.4)
Current field experience, mean years (SD)	16.0 (11.2)
Experience with EHRs, mean years (SD)	14.7 (6.4)
Time working at IH, mean years (SD)	15.4 (10.1)

Source: Descriptive data collected at the end of each interview.
Notes: *Number and percentage for role exceeds 14 and 100% respectively because some interviewees had more than one role.

CHAPTER 7

DISCUSSION

7.1 Summary

The U.S. has reached widespread adoption of EHR systems, and, as a result, the literature exploring their impact on quality, productivity, and safety outcomes has also increased. However, such evaluations fall short on the use of standardized measurements that have the ability to detect diverse impacts introduced by health IT interventions. In addition, the ongoing effects of EHR implementations are frequently ignored since studies available rarely test the impact of their interventions over time, and have not focused on the identification of organizational factors potentially affecting the outcomes during the implementation. In the traditional paradigm of health IT evaluations, the lack of robustness of study design limits the detection of time-sensitive effects and the reporting of standardized measurements that can facilitate comparison of outcomes across studies, leaving unanswered questions as to the impact of health IT interventions.

In this dissertation we explored the feasibility of detecting a broad range of time-sensitive performance changes during a commercial EHR implementation on quality, productivity, and safety outcomes, by monitoring a large set of outcomes measures likely impacted by such interventions. To allow a more general understanding of health IT impact, we also explored the feasibility of identifying factors, associated or not with the new EHR implementation, that may introduce time-varying effects, and therefore may impact care outcomes. Based on previous literature reporting and input from experts in the field, we identified a wide range of relevant outcome measures for assessing EHR implementations. Therefore, rather than arbitrarily selecting a narrow set of outcome measures, we monitored a large-scale commercial EHR implementation covering a wide range of relevant outcomes. We also monitored these outcomes over time in order to detect ongoing effects commonly introduced by health IT interventions. This approach is aligned with recommendations from experts in the field who suggest that more robust evaluations are necessary to increase the understanding of the impact of health IT adoption. According to these experts, the evaluations must include multiple components of the health care value chain, and consider the ongoing effects of health IT adoption, since health IT value accrues over time [1]. Furthermore, in order to make general conclusions about health IT impact, other aspects not directly related to IT must be explored, as demonstrated by studies of IT adoption in other sectors of the economy [2-3].

In an attempt to increase the understanding of the impact of EHR adoption and empower researchers in charge of future evaluations, we have conducted four studies that follow a logical flow. First, we conducted a secondary analysis of a previously published systematic review and identified the most commonly reported outcomes for assessing health IT interventions (Chapter 3). However, this initial inventory did not provide comprehensive coverage of productivity and safety care processes and the studies reporting these outcomes did not provide evidence of their ability to detect health IT impact. Therefore, we investigated the relevance of these outcomes as perceived by experienced health care leaders and national informatics experts, and identified other relevant outcomes not commonly reported in the literature (Chapter 4). After having identified a wide range of relevant measures converging several quality, productivity, and safety care processes, we conducted the largest evaluation of a commercial EHR implementation so far, to test the ability of our method to detect various patterns of impact and time-sensitive effects. The method was successfully tested and we identified various mixed-effects and patterns of impact with far-reaching implication for health care leaders across the country (Chapter 5). Despite the diverse set of impacts detected, we still had not elicited other factors directly or indirectly related to the new EHR implementation that could have affected these outcomes alongside the new EHR. We then conducted a qualitative analysis guided by the results of our longitudinal quantitative evaluation and identified several factors perceived by users that affected the outcomes during the new EHR implementation (Chapter 6). These studies demonstrated that commercial EHR implementations in large care delivery systems introduce a wide range of performance changes and that our proposed methodology allows detection of these changes over time. They also demonstrated that the breadth and depth of the impact will not be covered by monitoring only the primary outcomes, but also by identifying and monitoring organizational factors affecting them. These factors may impede users' proficiency in the new system, leading to decreased efficiency and the introduction of negative impacts on care outcomes, and deserve further attention from the broader informatics community.

7.2 Significant Contributions

This research delved into the complexity of care processes and several sociotechnical factors that need to be systematically monitored in order to detect the various impacts introduced by EHR implementations, and provides significant contributions to the informatics community. The first study proposes the first inventory of health IT impact measures and a taxonomy to classify these measurements into various measurement types. The second study expands the previous one by providing a more robust inventory of relevant outcome measures for assessing EHR implementations with data readily available in electronic format. The improved inventory and taxonomy will help researchers to find gaps in their measurement approaches and report more standardized measurements to facilitate comparison of outcomes across studies by future systematic reviews – and potential meta-analysis. As demonstrated by the third study, the use of our systematic methodology will guide health care leaders, health IT vendors, and the broader medical and informatics communities by informing *what* and *how* to continuously monitor future similar implementations. The method can be used to detect unexpected effects earlier and more precisely, allowing the implementation of effective responses to mitigate negative impacts. Furthermore, the use of data readily available in electronic format from two distinct EHR systems (Intermountain's legacy systems and Cerner's EHR) demonstrates that our proposed measures do not depend on a specific EHR, which increases generalizability of our method to other settings. The fourth study is the first one in the health care industry to explore organizational factors that may have affected the performance changes observed during an EHR implementation. It also reports multiple potential covariates with data available in electronic format for continuous monitoring of these factors in future evaluations.

Last, this dissertation implies that the use of our method in future evaluations and the continuous identification of relevant measures, factors, and covariates, will be of paramount importance to progressively lead us to a better understanding of the impact of IT interventions in health care.

7.3 Limitations

The research described in this dissertation has several limitations. We acknowledge that our proposed inventory of measures may not cover all relevant care processes likely impacted by health IT interventions, and that measurements that are relevant today may not be relevant tomorrow. The inventory may need to be revised and updated in the future.

Intermountain Healthcare has extensive experience with informatics applications and the commercial EHR implemented replaced homegrown legacy 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.

Due to ongoing mappings between Intermountain's legacy systems and Cerner's EHR databases, we were not able to include over half of the measures in our inventory and may not have detected all performance changes that happened during the implementation.

Information obtained in the interviews in region 4 was susceptible to the personal biases of each informant. We were able to interview only 14 informants from only one implementation region, which may have compromised identification of other factors.

Lastly, although we identified several covariates to test the hypothesis that the factors identified can affect the outcomes measured, we were not able to add these covariates to our methodology in the present research in order to test this hypothesis.

7.4 Future Directions

The research described in this dissertation could lead to important changes in future evaluations of IT interventions in health care. We propose the use of our measures along with their proposed nomenclature in future evaluations of health IT adoption to facilitate standardized reporting of outcomes in future studies. We also propose a continuous identification of new measurements and the development of an ontology that maps these measures to standardized medical vocabularies included in the Unified Medical Language System (UMLS) [4], to facilitate measurement and reporting of outcomes in future evaluations. To researchers conducting future systematic reviews of health IT evaluations, we propose the use of our taxonomy to facilitate classification and comparison of outcomes across future studies for the identification of patterns of impact and outcomes more likely to be negatively or positively affected by health IT interventions.

Rudin et al. [1] estimate that without improved research designs, around 100 hypotheses per year will continue to be tested without providing any valuable knowledge. As demonstrated by this dissertation, EHR implementations introduce performance changes to multiple care processes, and such changes may affect care outcomes over time for several months. In order to avoid potential wasted time and research funding dedicated to hundreds of future evaluations that will add little or no value, we propose the use of our systematic methodology as a standard method for assessing health IT interventions. Without considering the ongoing effects of IT adoption in future evaluations, future systematic reviews will continue to lack essential information necessary to make more specific comparisons across studies, and therefore will continue to leave unanswered questions on the impact of health IT adoption. We hope that the several time-sensitive effects detected by our methodology can cause paradigm shift on the choice of research designs for health IT studies, producing more longitudinal evaluations as opposed to the frequently reported pretest-posttest studies. Also, in addition to including longitudinal evaluations and a wide range of outcomes, future studies must account for the influence of factors affecting the outcomes during EHR implementations. We propose future research exploring the impact of the factors identified in this dissertation and the continuous identification of other potential factors not detected by this research.

Lastly, with an increasing adoption of commercial EHR systems by large care delivery networks and academic medical centers [5], it is critical for health care organizations to systematically monitor their EHR implementations. Monitoring should be present not only during the transition phase, but also continuously in order to detect changes caused by new versions, implementation of new modules, subtle changes introduced through configuration (e.g., CDS alerts, order sets), system malfunction, and human adaptation. Such monitoring can serve the purposes of both improving future scientific evaluations and detection of unexpected effects that can potentially compromise the ability of an organization to continue to peruse optimal care during an EHR implementation. We recommend the development of a national real-time monitoring system that could be used for identification and comparison of unexpected effects introduced by health IT interventions. Such effects could be compared and shared among health care institutions for monitoring of deviations from baseline performance and implementation of effective strategies for mitigating negative impacts. This research builds the foundation for such a monitoring system.

7.5 References

[1] Robert S. Rudin P, Spencer S. Jones P, Paul Shekelle MD, Richard J. Hillestad P, and Emmett B. Keeler P. The value of health information technology: filling the knowledge gap. Am J Manag Care. 2014 Nov;20(11 Spec No. 17):eSP1-8.

[2] Brynjolfsson E. The productivity paradox of information technology. Commun ACM. 1993 Dec;36(12):66–77.

[3] Brynjolfsson E, Hitt LM. Beyond the productivity paradox. Commun ACM. 1998;41(8):49–55.

[4] The Unified Medical Language System. Accessed at https://uts.nlm.nih.gov/home.html on June 30, 2017.

[5] Jones SS, Rudin RS, Perry T, Shekelle PG. Health information technology: an updated systematic review with a focus on meaningful use. Ann Intern Med. 2014 Jan 7;160(1):48–54.