The strongest location-based relationships were found with physicians where they were more likely to move to the workspace from exam rooms and nurse stations. There appeared to be an information need requiring multiple moves to the nurse station in-between patient visits. A framework was developed combining statistical and computational techniques used for sequence analysis to predict physician behaviors and create a set of methods to develop quantitative metrics associated with clinical workflow as well as a set of interactive visualizations to convey feedback (summary of developed metrics) to the clinicians. This could be invaluable support tool in clinical practice. The derived measures via visualization of clinical workflow using sensor-based technology, can support researchers and clinical stakeholders, as they identify bottlenecks in the workflow process, which can be further investigated in greater detail using other complementary techniques such as, ethnography.

EHR Use and Clinical Performance

At ISMMS, data showed positive correlations between physician review of patient charts, and door-to-disposition time and with length of stay (LOS. Physician patterns of EHR use and direct patient care were consistent with shadowing sessions, showing some relationship of log data to clinical activity. However, RFID findings were inconsistent with shadowing sessions, suggesting individual differences in care are greater at this site than at the Site 2. EHR data also show increased time spent on documentation and chart review among physicians, which shows the need for their reliance on long-form documentation in order to manage and situate their activities.

This can partially be attributed to the workflow in academic medical centers. In other words, academic medical centers have a multi-layered process of iterative review with residents performing frontline clinical activity, supervised and guided by attending physicians. The downside, as highlighted from our results, is the potential impairment in performance (in terms of longer time involved in the care process).

In addition, the results also highlight the team-based care in complex distributed settings such as the ED, where multiple clinicians (including residents, nurses, pharmacists and attending physicians) are involved in the care process. The data generated during this care process show a non-linear fashion of data update. As a result, decisions are often delayed till there is appropriate updating of data. Multi-layered process of review may help improve patient safety (confirmed by shadowing sessions), and technological support (such as RFID) can be sort to offload some tasks, and scribers can be assigned for documentation task.

Use of Automated Technology to Off-load Clinician Tasks

Use of sensor-based technology at Mayo Clinic show that of the MU criteria, door to doctor time, could be automated with more accuracy, freeing doctors from extra task and cognitive load, and thereby contributing to reduction of ED overcrowding (increasing patient safety). However, during observations and sensor analysis, we found that this measurement was not precise, with significant variations in the time when the doctor sees the patient with respect to when the tagging records begins. The nature of workflow in the ED appear to be responsible for this variation. Similarly, decision time is also imprecise, given that the time when decision is made is not the same time when the physician enters in the computer. A more precise measurement scale needs to be developed.

OUTCOMES [MILESTONES]

1. *Perceived Influence of EHR on Clinical Workflow and Performance Metrics* as a result of EHR use and MU criteria compliance, at two clinical sites.
   Manuscript based on analysis of semi-structured interviews at both clinical sites on clinical workflow and Meaningful Use (MU) performance metrics was published in *Applied Clinical Informatics* journal (Denton, Soni, et al, 2018) and a poster at AMIA Conference Proceedings (Denton et al 2016).
2. *Shadowing data analysis to characterize two clinical workflows to understand the work process, including, interactions, interruptions, etc. within the complex organizational structure of individual environment.* With integration of data from two study sites, we characterized two distinct workflow models that provide an integrative framework for interpreting our data, including those from RFID location tracking, EHR data logs,

shadowing, and clinician interviews. A manuscript is being prepared for submission. A poster was also presented at the meeting of AMIA *Clinical Informatics* Conference (Soni, et al 2018).

3. *Demonstrating clinical relevance of developed visualizations for clinicians*
   We developed a web-based dashboard representing workflow metrics from RFID and EHR summary data for presenting derived metrics to clinical and administrative end users. Our goal is to provide value from the tracked data for clinicians who do not have ways of assessing and modifying their own behavior based on tracked data. It is also potentially useful for process analysis and behavior modifications based on technological changes or by discovering existing bottlenecks. Manuscripts were published in JBI (Frisby, et al 2017, Vankipuram et al, 2018) and in AMIA Conference Proceedings (Vankipuram, et al 2017)
4. *Analyzing EHRs log files for tracking clinical workflow at ISMMS to characterize the relationship between pattern of EHR use and performance.* Evaluation of the role of various EHR-based activities on the overall performance metrics in the ED resulted in a manuscript published in ACI (Kannampallil, et al 2018)
5. *Extrapolating qualitative workflow metrics from clinician location tracking data.* A manuscript published in the *JBI (Vankipuram, et al, 2018) and a book chapter (Vankipuram and Patel,2019)*.
6. *Simulation of clinical behaviors, specifically time spent at various locations and their impact on time to see patients to capture more precisely the impact of EHRs on performance.* Leveraging the transition probabilities of physician movements using RFID data to develop Monte-Carlo simulations to determine with a greater level of statistical certainty the time spent in locations or tasks prior to a patient examination in the ED workflow. Given the computation of transition probabilities, Monte Carlo simulations help in ascertaining time spent during a workflow process. Simulating a set of physician movements using transition probabilities is functionally equivalent to observing the behavior. As the transition probabilities are computed from a nearly year-long dataset, these patterns are likely to be consistent. This means that we can discover time taken or number of transitions made to reach some end location of interest (e.g., an exam room) to compute EHR to patient visit time. (Vankipuram and Patel, 2019)
7. *Combining multiple data sources.* Overlaying RFID, Shadowing and EHR log files from Mayo Clinic to develop a more comprehensive picture of clinical workflow, characterizing a fine-grained relationship between EHR work pattern and other performance measures. Overlaying location tracking RFID data on the physician shadowing data and EHR log files data provided us with a deeper insight into clinical flow and the impact of EHRs on the clinical activities. Time consuming human intensive analysis can be replaced by the use of technology. A manuscript was accepted for publication in *JBI* (Vankipuram et al 2018).
8. *Combining RFID and EHR log files from ISMMS to characterize the interaction pattern of nurses and physicians with components of EHR.* Combined 15 sessions of RFID and log files, we performed a combined analysis to evaluate the process by which clinicians split their time between patient care and EHR-based documentation activities A manuscript is under review. *(Kannampallil et al, 2019)*
9. Development of guidelines and recommendations. A set of preliminary recommendation guidelines based on findings from all studies are given below.

SIGNIFICANCE AND RECOMMENDATION GUIDELINES FROM FINDINGS

The primary purpose of this research program is to understand and improve clinical workflow—both from EHR-based perspective, and from a workflow perspective—in order to improve efficiency, quality, and safety. This will require the translation of easily available secondary data (e.g., EHR data logs, sensor-based data) into pragmatic information that can be used by clinicians during their clinical activities, and displayed through dashboard visualizations. Our findings regarding usability also highlight the need for on-going interface improvements; this primarily arises because new features and tools are constantly added on the EHR, increasing the learning curve for users, and potentially contributing to usability challenges. We used MU criteria as an external metric for evaluating clinical workflow. However, with changing perspectives on MU use and its role, new measures should be considered.

EHRs often act as an external decision support system (offloading extra cognitive load), as long as we are clear about what purpose they serve in various environments. EHRs support different activities in academic and non-academic environments, making it important not to evaluate and judge all EHRs on the same scale. Performance and efficiency are important, but they are not the only consideration. Academic medical centers have multiple functions including training, education, and collaboration; this improves the quality and safety of care. By managing complexity (not reducing it) through cognitive and technology support, we support both

learning and safety as well as improve resilience in the environment.

How can we leverage technology in the ED to increase efficiency without compromising safety (within a given margin of error)? Our findings suggest:

- Using automation such as tracking devices can increase efficiency without compromising safety
- Having scribes to help doctors in the ER will increase efficiency and reduce physician burnout rate, but may increase error due to reliance on ascribes to input information which may not be completely accurate. Often errors are caught when doctors do the documentation themselves (use of metacognition). How can we offset this issue of "error check"?
- Collecting secondary data from audit trails (unobtrusive and automated)
- Building support for data capture in real-world clinical environments. Standardized, but extensible and flexible infrastructure that can be used for data capture (e.g., generic templates that can be used in a mobile device)

The complexity and demands placed upon physicians within academic ED settings, characterized by team communication, contributes to error recovery as collective knowledge and expertise provides more opportunities for error detection to occur between physicians. Interruptions and multitasking not just compromise safety by increasing cognitive load, but also provide a source of error detection and correction through team work (learning through education and training). ISMMS' team-based model of error detection and correction may outweigh the capacity for recovery of individuals when working alone, as observed at Mayo.

Importance of presenting information through data analytics and visualization to ER physicians.

- Our work has demonstrated a series of methods that can leverage these technologies to derive deeper insights into clinical workflow and associated issues and bottlenecks. The main advantage of data analytical techniques is the potential condensation of complex analyses into smaller nuggets of relevant quantifiable information about behavior and workflow that can be targeted to specific clinicians or groups of clinicians (i.e. nurses, physicians etc.).
- Visual analytics and visualizations can help reduce the burden and provide a series of techniques (as described in this report) that simplify the process of communicating results of workflow analysis to the target clinicians. It also allows informaticians to modify the presentation of the same set of results to different end-users. For example, summaries of analyzed workflow behavior can be presented in graphical ways to some physicians for quick perusal while including numeric content and more complex visualizations for administrators or researchers. This can help broaden the types of health care providers and administrators who can benefit from such visual analytics.

Mining EHR data logs for characterizing clinical and EHR workflows

- Data logs are products of user interactions with EHRs. They provide a simple and efficient mechanism to understand and characterize human interaction behaviors and EHR workflows. They are however challenging for data analysis as they require significant clean up and processing before they can be useful. Data logs can also be effective complementary to other sources of data. For example, we used data logs in combination with RFID to track both the physicians' clinical workflow and their EHR workflow at the same time, providing valuable insights. Based on our series of studies that used EHR data logs independently and with RFID data, we found patterns of EHR use, evaluated ER efficiency metrics based on EHR usage, and clinical workflow activities of clinicians.

LIMITATIONS AND LESSONS

Our studies have a number of limitations. First, we studied two clinical environments with two different systems, with generalizability limitations, except for developed methodology. These studies need to be validated at other EDs and beyond. Second, we chose to focus on the attending physician mostly, as they are ultimately responsible for all decisions regarding the patient, although an attending physician's workflow is also determined by other clinicians and the nature of the support provided by the team.

Third, this study was based on a small sample of physicians and a very large sample of patients at two different institutions. However, given that we computed EHR-based activities separately for each segment of the ED-based performance metrics, the potential associations are still valid. We did not capture the patient demographics or their clinical conditions for our analysis. Accounting for the differences in clinical conditions in the analysis could possibly weaken the associate effects that were observed.

Fourth, there are many challenges to conducting investigations in natural environment, where unanticipated events emerge, such as, overnight decision to change the use of technology (EHRs, sensor technology], brutally affecting our work, and so, the investigators have to be prepared to adapt to the situation by modifying the studies "on the run" without losing time. The PI has to be always prepared to adapt quickly and effectively and provide leadership role of the team

Finally, our research show that quantitative studies [data logs] are valuable in getting amount of time clinicians spent on various sections of EHR systems, but the context was missing. Qualitative studies provide that added value of not only contextualizing it [ethnography], but also interpreting the data with respect to clinician locations [RFID] in the ED, thereby providing a more composite picture of clinical workflow

LIST OF PUBLICATIONS: OUTPUTS

Journal Papers

- Kannampallil, TG, Abraham J, Patel VL. Methodological framework for evaluating clinical processes: A cognitive informatics perspective. Journal of Biomedical Informatics, Special issue on Cognitive Informatics Methods for Interactive Clinical Systems 2016;64, 342-351. PMID: 27847328
- Frisby J, Smith V, Traub S, et al. Contextual Computing: A Bluetooth-based Approach for Tracking Healthcare Providers in the Emergency Room. Journal of Biomedical Informatics 2017;65:97-104. PMID: 27913245
- Vankipuram A, Traub S, Patel VL. A method for the analysis and visualization of clinical workflow in dynamic environments. Journal of Biomedical Informatics Vol. 79, March 2018, Pages 20-31. PMID: 29410146
- Kannampallil TG, Denton CA, Shapiro JS, et al. Efficiency of Emergency Room Physicians: Insights from an Observational Study using EHR Log Files. Applied Clinical Informatics 2018; 9(1):99-104. PMID: 30184241
- Denton CA, Soni HC, Kannampallil TG, et al. Emergency Physicians' Perceived Influence of EHR Use on Clinical Workflow and Performance Metrics. Applied Clinical Informatics, 2018;9(03):725-733. PMID: 30208497
- Vankipuram A, Patel VL, Traub S, et al. Overlaying Multiple Sources of Data to Identify Bottlenecks in Clinical Workflow. Journal of Biomedical Informatics: X. 2019; 28:100004.
- Kannampallil TG, Denton CA, Shapiro JS, et al. A multi-scaled approach for characterizing physician and nurse activities using EHR logs and RFID tracking. JAMIA Open 2018 Dec. [Under review]

Book Chapters

- Vankipuram A, and Patel VL, Automated location tracking in clinical environments. A review of systems and impact on workflow analysis in the ER. In: Zheng K, Westbrook J, Kannampallil T, Patel VL, eds. Cognitive Informatics. Reengineering Clinical Workflow for More Efficient and Safer Care. UK: Springer; 2018: Chapter 13.

Conference Proceedings

- Patel VL, Kannampallil TG, Vankipuram A. Automated Monitoring of Clinical Workflows: Opportunities and Challenges. In: Proceedings of International Symposium on Human Factors and Ergonomics in Healthcare; 2016; San Diego, CA. Publishers; Human Factors and Ergonomics; 2016 July 27-31; San Diego, CA.
- Kannampallil TG, Zheng K, Patel VL. Analysis of Human Interactive Behavior for Improving Health IT Usability and Minimizing Patient Safety Risks. Presented as a tutorial at AMIA Annual Symposium; 2016; Nov 12-16, Chicago, IL.
- Kannampallil TG, Zheng K, Patel VL. Analysis of Human Interactive Behavior for Improving Health IT Usability and Minimizing Patient Safety Risks. Instructional Workshop at AMIA Annual Symposium (AMIA); 2017 Nov 4-8; Washington, DC.
- Vankipuram A, Traub SJ, Patel VL. Clinical Workflow Visualization: Representation of Clinician Activity from Location Tracking Data. In: Proceedings of the American Medical Informatics Association (AMIA) Annual Symposium; 2017 Nov 4-8; Washington, DC. AMIA publishers; 2017.

- Patel VL. Innovative Methods based on R01 award supported by AHRQ. A Webinar presented to the Division of Health IT Team, AHRQ, 2018 March 21.
- Dymek C, Tai-Seale M, Patel VL, et al. Panel on EHR Log Data: An Untapped Health Data Goldmine for Clinical Informatics Research. In: Proceedings of the Annual Meeting of the American Medical Informatics Association (AMIA); 2018 Nov 3-7; SFO. AMIA publishers; 2018.

Tutorial/Instructional Workshop

- Kannampallil TG, Zheng K, Patel VL. Analysis of Human Interactive Behavior for Improving Health IT Usability and Minimizing Patient Safety Risks. Instructional Workshop at AMIA Annual Symposium (AMIA); 2018 Nov 3-7; San Francisco, CA.

Conference Abstracts (Posters)

- Denton CA, Nimo G, Shapiro J, et al. Perceived Effects of Meaningful Use Compliant Electronic Health Records on Clinical Workflow: A Preliminary Analysis. In: International Symposium on Human Factors and Ergonomics in Healthcare; 2016 July 27-31; San Diego, CA.
- Denton CA, Shapiro J, Nimo G, et al. Perceived Effects of Meaningful Use of Electronic Health Records on Clinical Workflow. In: Proceedings of the Annual Meeting of American Medical Informatics Association (AMIA); 2016 Nov 12-16; Chicago, IL.
- Soni HC, Denton CA, Serrichio A, et al. Clinicians' Perception of EHRs in Emergency Department Workflow. In: ASU BMI-Mayo Clinic Poster & Employer Networking Event, 2017April 21; Mayo Clinic Campus, Scottsdale, AZ.
- Vankipuram A, Traub SJ, Patel VL. ClinicalWorkflow Visualization: Representation of Clinician Activity from Location Tracking and EHR log file Data. In: ASU BMI-Mayo Clinic Poster & Employer Networking Event, 2017 April 21; Mayo Clinic Campus, Scottsdale, AZ.
- Soni H, Vankipuram A, Denton CA, et al. Characterization of Clinical Workflow and Electronic Health Records in Emergency Medicine. In: Proceedings of Clinical Informatics Conference of American Medical Informatics Association, 2018 May 9; Scottsdale, AZ.

Seminars

- Patel VL. Sensor-based Monitoring of Clinical Workflows in Emergency Rooms: Opportunities and Challenges. Invited Speaker for Informatics Intervention Research Collaboration series presented by Columbia University's Department of Biomedical Informatics, 2016 June 21.
- Patel VL. Sensor-based Monitoring of Clinical Workflows in Emergency Rooms: Opportunities and Challenges. Invited Speaker for Center for Behavioral Cardiovascular Health series presented by Columbia University Medical Center, 2016 September 26.

Dissertation

- Vankipuram A. Utilization of Automated Location Tracking for Clinical Workflow Analytics and Visualization (Doctoral Dissertation: Advisor: Vimla, L Patel). Arizona State University; Nov. 2018. Parts of the work reported in this Dissertation was supported by Agency for Healthcare Research and Quality (AHRQ) through our collaborating site, located at Mayo Clinic, Phoenix, AZ.

Manuscripts in Progress

- Patel VL, Denton CA, Soni HC, et al. Electronic Health Record System and its Impact on Emergency Department Clinical Workflow in Academic and Non-Academic Hospital Environments. [J Patient safety]
- Patel VL, Kannampallil T.G., Vankipuram A., et al. Nature of the Beast: Recommendations for Efficient EHRs with Low Safety Risks in Emergency Care [BMC Medical Informatics and Decision Making

REFERENCES

1. Institute of Medicine. The Computer-Based Patient Record: An Essential Technology for Health Care Revised Edition. Washington, D.C.: National Academy Press; 1997.
2. Blackford M, Bloomrosen M, Dente MA, et al. Enhancing Patient Safety and Quality of Care by Improving the Usability of Electronic Health Record Systems: Recommendations from AMIA. Journal of the American Medical Informatics Association. 2012. PMID: 23355463
3. Blumenthal D. Stimulating the Adoption of Health Information Technology. New England Journal of Medicine. 2009;360:1477-9. PMID: 19321856
4. Jha AK, DesRoches CM, Kralovec PD, et al. A Progress Report on Electronic Health Records in US Hospitals. Health Affairs 2010;29(10):1951-7. PMID: 20798168
5. Institute of Medicine. Health IT and Patient Safety: Building Safer Systems for Better Care. Institute of Medicine; 2011.
6. Linder JA, Ma J, Bates DW,et al. Electronic Health Record Use and the Quality of Ambulatory Care in the United States. Archives of Internal Medicine. 2007;167(13):1400-5. PMID: 17620534
7. Hogan SO, Kissam SM. Measuring Meaningful Use. Health Affairs. 2010;29(4):601-6. PMID: 20368588
8. Patel VL, Arocha JF, Kaufman DR. Diagnostic Reasoning and Medical Expertise. Psychology of Learning and Motivation- Advances in Research and Theory 1994;31:187-252.
9. Strauss A, Corbin JM. Basics of Qualitative Research: Grounded Theory Procedures and Techniques. Thousand Oaks, CA: Sage Publications, Inc.; 1990.
10. Zheng K, Haftel HM, Hirschl RB, et al. Quantifying the impact of health IT implementations on clinical workflow: a new methodological perspective. J Am Med Inform Assoc. 2010;17(4):454–61. PMID: 20595314