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A Multi-Method Evaluation Of A Guideline Based Clinical Decision Support Intervention On Provider Ordering Behavior, System Acceptance And Inter-Professional Communication

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Abstract

Background and aims: Unnecessary variation in the delivery of patient care is well documented in the medical literature; evidence-based clinical practice is critical for improving the quality of care. Clinical decision support systems (CDSS) are promising tools for improving the systematic integration of evidence into clinical practice. This study evaluated a CDSS in a domain of care that had not yet been explored—namely, decision support for venous catheter selection. This dissertation study aimed to (1) evaluate the effect of this CDSS on provider ordering behavior before and after implementation and explore the differential impact of this tool by provider type and service and (2) identify organizational, individual, usability, and workflow factors that impact CDSS acceptance by physicians and advanced practice nurses and to elicit information about the impact of this system on communication between providers and the nurse-led vascular access team. Methods: This was a multi-method study. Aim one was single group pre-post analysis of longitudinal data. Variables included those related to patient and provider level factors. The main analysis was conducted with linear regression models with random effects to account for clustering of data. We conducted semi-structured interviews for aim two and use conventional qualitative content analysis to identify themes. Results: We found mixed results in the impact of the CDSS on provider ordering behavior. While the CDSS did not have an impact on the number of venous catheters ordered, we saw a statistically and clinically significant decrease in the proportion of double lumen catheters ordered. Findings for the qualitative aim showed that the CDSS improved process efficiency and inter-professional communication. We found that it also facilitated education for evidence based practice for novice providers. Discussion: This dissertation study showed a clear impact of the CDSS on double lumen catheter ordering, which has implications for patient outcomes. Furthermore, we found impacts by provider type. Additional work is needed to evaluate this CDSS in other settings and to further assess differential impacts by provider type.

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A MULTI-METHOD EVALUATION OF A GUIDELINE BASED CLINICAL DECISION SUPPORT INTERVENTION ON PROVIDER ORDERING BEHAVIOR, SYSTEM ACCEPTANCE AND INTER-PROFESSIONAL COMMUNICATION

Emilia J. Flores

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DEDICATION

To Anna, with all my love. One lifetime isn't enough.

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ABSTRACT

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Background and aims: Unnecessary variation in the delivery of patient care is well documented in the medical literature; evidence-based clinical practice is critical for improving the quality of care. Clinical decision support systems (CDSS) are promising tools for improving the systematic integration of evidence into clinical practice. This study evaluated a CDSS in a domain of care that had not yet been explored—namely, decision support for venous catheter selection, which is an important decision point since risk for adverse patient outcomes differ between venous catheter types. This dissertation study aimed to (1) evaluate the effect of this CDSS on provider ordering behavior before and after implementation and explore the differential impact of this tool by provider type and service and (2) identify organizational, individual, usability, and workflow factors that impact CDSS acceptance by physicians and advanced practice nurses and to elicit information about the impact of this system on communication between providers and the nurse-led vascular access team. **Methods:** This was a multi-method study. Aim one was a single group pre-post analysis of longitudinal data. Variables included those related to patient and provider level factors. The main analysis was conducted with linear regression models with random effects to account for clustering of data. We conducted semi-structured interviews for aim two and used conventional qualitative content analysis to identify themes. **Results:** We found mixed results in the impact of the CDSS on provider ordering behavior. While the CDSS did not have an impact on the number of venous catheters ordered, we saw a statistically and

clinically significant decrease in the proportion of double lumen catheters ordered. Findings for the qualitative aim showed that the CDSS improved process efficiency and inter-professional communication. We found that it also facilitated education for evidence based practice for novice providers. **Discussion:** This dissertation study showed a clear impact of the CDSS on double lumen catheter ordering, which has implications for patient outcomes. Furthermore, we found impacts by provider type. Additional work is needed to evaluate this CDSS in other settings and to further assess differential impacts by provider type.

TABLE OF CONTENTS

LIST OF TABLES

Note: the table prefix “A” refers to “Aim”. A1.1 refers to data related to Aim 1.1, while A1.2 refers to data related to Aim 1.2.

LIST OF FIGURES

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CHAPTER 1

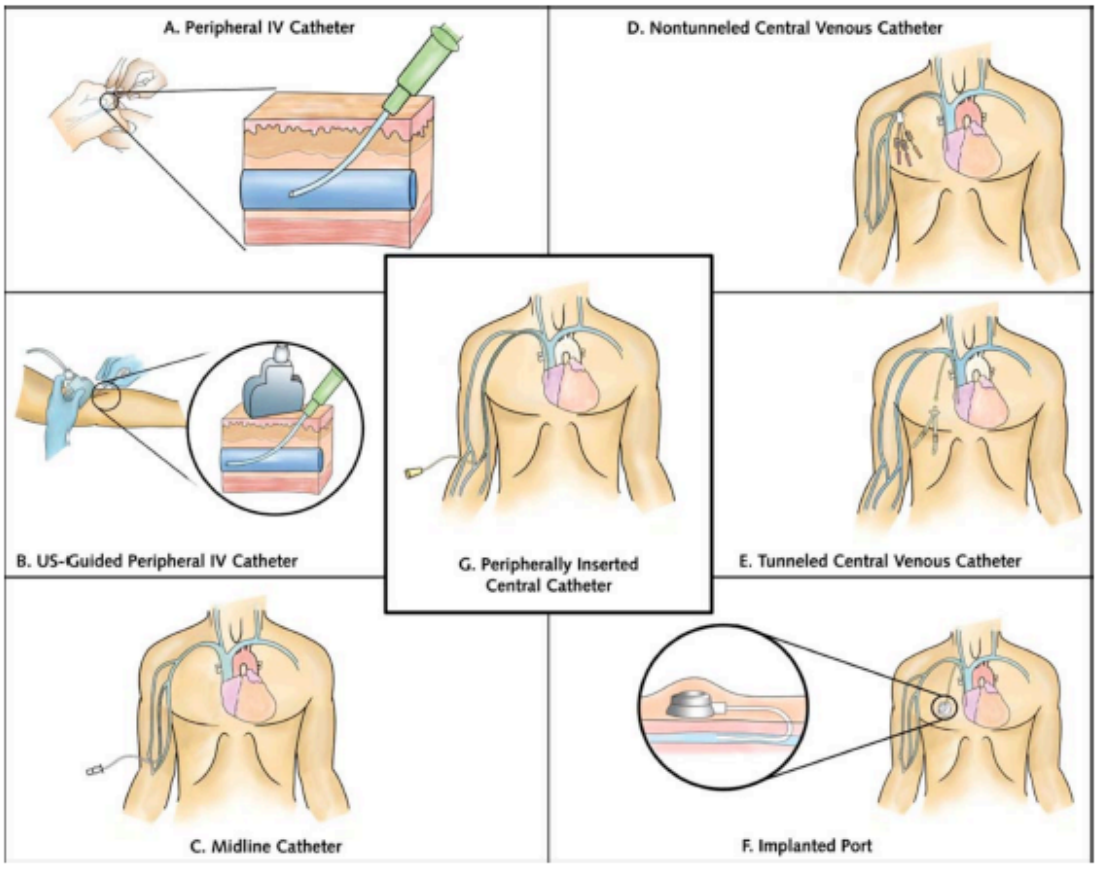
Unnecessary variation in the quality of patient care is well documented in the medical literature. In 2001, the Institutes of Medicine's *Crossing the Quality Chasm* report cited 70 examples of high-quality studies demonstrating significant variation in care quality.[1,2] Evidence-based clinical practice, defined as the integration of evidence from systematic research into clinical judgement,[3] is viewed as critical for improving the quality of care and reducing unnecessary variation. However, despite evidence for significant differences in care quality and the availability of high-quality clinical practice guidelines, adherence to recommendations is still suboptimal. There are a variety of methods for improving the uptake of evidence into practice. Clinical decision support systems (CDSSs) are promising tools for improving the systematic integration of evidence into clinical practice.[4] In their report the Institutes of Medicine called for the use of CDSSs as a means for implementing evidence into clinical practice.[5] Over the decades, strong evidence has emerged regarding the ability of CDSSs to change provider behavior and improve evidence-based ordering of treatments or procedures. A meta-analysis from 148 randomized control trials in 2012 by the Agency for Healthcare Research and Quality (AHRQ) concluded that overall, providers using CDSSs were 1.6 times more likely to order correct therapies compared to control groups.[4,6]

Despite strong evidence for CDSSs, there are still many opportunities within the care delivery process to study the application of these systems. Additionally, gaps remain in understanding the contextual factors associated with system acceptance and use. This study evaluated a CDSS in a domain of care that had not yet been explored—namely, decision support for venous catheter selection.

Venous Catheter Selection: A Clinical Practice Decision with Patient Risk

The process for selecting a venous catheter contains several decision points that would benefit from the use of a CDSS. Multiple vascular access device options exist (Figure 1), with risk for complication varying significantly across the spectrum of catheter types.[7] The clinical decision-making process for catheter selection is nuanced, but guidelines and recommendations exist for guiding providers in the appropriate selection of devices. But despite these guidelines, research has shown that significant variation exists in this important healthcare decision.

Figure 1: Vascular Access Device Types[24]



Of the seven main options for catheter selection, the last decade has seen a significant increase in the use of **peripherally inserted central line catheters (PLC) (Figure 1, box G)**. Research findings have shown that this venous catheter type has the highest risk for venous thromboembolism (VTE), compared to all other catheter types, and a similar risk for central line associated bloodstream infection (CLABSI) compared to other central venous catheters.[8–14] These conditions have long been recognized as major patient burdens by numerous public agencies and private organizations, including the Agency for Healthcare Research and Quality (AHRQ), Centers for Disease Control and Prevention, and The Joint Commission.[15–17] VTE and CLABSI have significant patient morbidity and mortality risk. VTE 30-day mortality estimates range between 10%-30%[18,19] and 30-day hospital readmission rates range between 22%-32%.[20] CLABSI can increase hospital length of stay by up to six days in the non-ICU setting.[21,22] Complication risks can be mitigated by a number of means, including use of specialized vascular access placement teams and avoiding short term use of PLCs when clinically possible[23]. However, experts recommend adherence to best practices and evidence-based recommendations for PLC indication as a first line of defense in risk management.[24]

Despite evidence for PLC-associated complications and the availability of lower risk catheter options (i.e. Midline Catheter (MLC); Figure 1, box C), **usage of PLCs has increased dramatically over the past decade, primarily due to process and provider factors**.[8, 24,26–28] Compared to other central venous catheters, PLCs have lower insertion costs, lower rates of insertion-related complications, and, in many settings, PLCs are easier for ordering providers to request due to the existence of specialized, nurse-led vascular access teams that manage all aspects of catheter placement. Another key reason potentially explaining the popularity of these devices is a lack of provider understanding regarding device risks.[13,27] A survey of five health systems, representing 10 hospitals, found major gaps in provider knowledge regarding PLC

indication and complication risks, with almost 70 percent of respondents erroneously indicating that PLCs were less likely to cause bloodstream infection than other central venous catheter types.[27]

Despite much focus from government agencies, health systems, and academia, reducing care variation through the adoption of evidence-based practice continues to be a major challenge for our healthcare system. In this study, we use as an exemplar the implementation of an evidence-based clinical decision support system (CDSS) intervention designed to support decision-making for venous catheter device selection.

Implementation of an Evidence-Based Guideline CDSS Intervention

Recognizing the potential for overuse of PLCs and the associated risk for adverse patient outcomes, in 2012 clinicians at the University of Pennsylvania Health System (UPHS) created a set of evidence-based recommendations to support provider decision-making for vascular catheter selection. These recommendations focused on helping providers decide between PLCs and midline catheters (MLC): MLCs can be used in place of PLCs in many clinical situations and have a lower risk profile. In November of 2013, these recommendations were translated into computer readable format and implemented within a CDSS. This system was embedded within existing provider workflow and replaced the manual means of communicating device requirements to the nurse-led vascular access team.

Two versions of this system were ultimately implemented. **Version one**, implemented in November 2013, contained fields for collecting relevant patient information (i.e. medication type and duration) and a field for indicating the required number of device lumens (single lumen or double-lumen). Given the strong evidence for greater adverse outcomes for double-lumen PLCs compared to single lumen[13,29–31], the CDSS designers chose to implement the lumen field using a

check box. The order would default to single lumens unless the provider checked the box to indicate that a double-lumen device was required. The use of default options has been well documented in the literature as an effective strategy for behavioral change.[32–34] **Version two** was implemented in August 2014, nine months after version one. Key changes made in version two included the automation of one field to auto-populate patient data directly from the EHR and the addition of another field to facilitate scheduling of catheter placement.

Specific Aims and Methods

This quasi-experimental study assessed the effect of this CDSS intervention on provider ordering behavior. Additionally, the study identified individual and system level factors affecting provider acceptance and elicited information regarding the impact of this intervention on inter-professional communication.

Aim one: To evaluate the effect of the CDSS for vascular catheter selection on **provider ordering behavior before and after implementation.**

Measures 1.1-1.4 below were used to assess provider ordering behavior.

1.1. **Orders**: Proportion of PLC orders of all catheter orders.

1.2. **Discontinued Orders:** Proportion of discontinued catheter orders.

1.3. **Double-lumen PLC Orders:** Proportion of double-lumen PLC orders of all PLC orders.

1.4. **Order concordance:** Proportion of MLC concordance, which is defined as the proportion MLC orders for which the provider follows CDSS recommendations.

1.5. **Exploratory:** The measures (1.1 and 1.3) were explored for variation by provider type and service

Measures 1.1-1.3 were assessed in the following ways:

(1) Comparing measures at baseline (pre-intervention) with measures after the implementation of CDSS version one (post-intervention).

(2) Comparing measures at baseline (pre-intervention) with measures after the implementation of CDSS version two.

Aim 1.4 was assessed by comparing the proportion of order concordance after the implementation of version one with proportion of order concordance after the implementation of version two.

A total of two years and nine months of data from the Hospital of the University of Pennsylvania (HUP) was used for this analysis; one year of base line data (pre-intervention) and nine and twelve months of post-intervention data from versions one and two, respectively. All data used for this aim was *retrospectively* collected. For this quasi-experimental study, we used descriptive analysis and multivariate regression models with random effects to assess changes over time.

Aim two: To identify organizational, individual, usability, and workflow factors that impact CDSS acceptance, which we defined for this study as the willingness of users to use the system for the task that it was designed to support[35], by physicians and advanced practice nurses and to elicit information about the impact of this system on communication between providers and the nurse-led vascular access team. For this qualitative aim, semi-structured interviews were used to collect data from providers (physicians and nurse practitioners) within one medical specialty and from nurses in the vascular access team.

Definition of Key Terms

CDSS: Clinical decision support system, defined as electronic system designed to aid clinicians in clinical decision making.[4]

Basic electronic health record system: An electronic health record system that provides functionality for electronic capture of patient clinical and demographic information, provider order entry, and lab and report management, as well as billing information.

Clinical Practice Guideline (CPG): Scientifically developed rules and statements to assist providers in making appropriate health care decisions for specific clinical circumstances.[36] CPGs are developed from policy statements made by professional organizations, which are based on the synthesis of primary research studies and systematic reviews and meta-analysis of evidence.[4]

Comprehensive electronic health record system: Functionality includes decision support features (e.g. clinical guidelines, reminders, drug allergy results, drug-lab interactions, drug dosing support) and advanced provider order entry (e.g. lab reports).

Evidence Based Practice: "Conscientious, explicit, and judicious use of current best evidence in making decisions about the care for individual patients."[37]

Facilitator: Any factor that promotes or enables acceptance of the CDSS intervention

Implementation (research evidence into practice): Moving research into practice, with the goal of providing evidence-based information to providers and stakeholders with the intent of improving healthcare decision making;[38] Similar to uptake (see below).

Implementation Research: The study of "methods to promote the systematic uptake of research findings into routine practice to improve the quality and effectiveness of health services."[39]

Midline catheter/MLC: Midline catheter (MLC) are venous catheter devices between 7.5 to 25 cm in length and are placed in the antecubital fossa area in the basilic or cephalic vein. The important distinction for MLC catheters is that they *terminate just short of the subclavian vein*.[24] MLCs are

preferred over PLCs in certain cases, depending on duration of treatment, type of infusate, number and compatibility of medications to infuse, and patient characteristics.[24]

PLC: Peripherally inserted central catheter. "Long vascular access devices (>45 cm) are inserted into peripheral veins of the upper arm in adults and advanced so that the tip of the catheter resides in the lower portion of the superior vena cava or upper portion of the right atrium."[24] PLCs are a type of central venous catheter.

Structured Care Protocol: A local or site specific adaptation of a clinical practice guideline.[4]

System Use versus Acceptance: System use is related to actual system use (behavior) whereas acceptance is related to the intention to use.

System Workaround: "Observed or described behaviors that may differ from organizationally prescribed or intended procedures. They circumvent or temporarily 'fix' an evident or perceived workflow hindrance in order to meet a goal or to achieve it more readily."[40]

Uptake (clinical practice guidelines and knowledge): "Acquisition of research knowledge, and its utilization in action and decision-making."[41] Similar to implementation (see above).

CHAPTER 2: REVIEW OF THE LITERATURE

Adoption of evidence-based recommendations into clinical practice is a challenge for the US healthcare system, which has significant impacts on the quality of patient care. The Institutes of Medicine (IOM) defines quality of care as "the degree to which health services for individuals and populations increase the likelihood of desired health outcomes and are consistent with *current professional knowledge*".[42] Since the IOM's publication of *Crossing the Chasm* in 2001,[5] which served to highlight the significant quality gaps in the US healthcare system, reducing variation and improving the quality of care delivery has received increasing interest from healthcare stakeholders. Nonetheless, research continues to show that deficiencies in healthcare quality exist, especially in the area of evidence-based practice. Schuster and colleagues demonstrated that a significant percentage of patients do not receive care that is consistent with current evidence, with as many as 30% of patients in the acute care setting receiving care that is actually harmful.[43] McGlynn and colleagues assessed the extent to which recommended care is provided within a broad range of conditions and found that overall, 55% (CI: 54.3%-55.5%) of patients received care consistent with recommendations and guidelines, but these numbers varied substantially depending on the population and condition.[1] There are certainly challenges, for both providers and patients, in adhering to all relevant clinical practice guidelines, especially for older patients and for those with multiple chronic conditions.[44] Many guidelines address single topics/disease areas,[45] yet approximately 80% of adults above age 65 have more than one chronic condition.[46] Additionally, research from the Dartmouth Atlas Project showed that even after controlling for illness and patient preference, unexplained variation in the use of clinical practice guidelines by providers still exists.[48]

This study seeks to evaluate the effect on provider behavior of a clinical decision support intervention aimed at aligning provider decision-making with evidence-based recommendations.

The design of this study was informed by the field of implementation science, which is an area of research directly involved in the study of methods for improving the adoption of evidence into practice.[39]

In the following sections, we provide an overview of implementation science, theoretical foundations, interventions and outcomes and an overview of the types of CDSSs and outcomes.

Implementation Science: Methods to Promote the Uptake of Evidence into Practice

Eccles and Mittman defined implementation science as the "scientific study of methods to promote the systematic uptake of research findings into routine practice to improve the quality and effectiveness of health services."[39] The following section provides an overview of the theoretical foundations of this field, interventions that have been used to facilitate the uptake of research into practice, and intervention outcomes.

Theoretical foundations. Implementation science is a multi-disciplinary field, with theories and models originating from diverse disciplines such as nursing, cognitive psychology, education, marketing, decision-making science, and organizational research and the list of theories and frameworks is extensive. Due to the large inventory of theories, models, and frameworks available for implementation science, a detailed discussion of each is beyond the scope of this paper. We will focus on efforts to distil and consolidate theories and models for ease of use by researchers.

Implementation science: attempts to improve accessibility of theories and models. In recent years there has been much work in improving the organization of this information to improve accessibility for researchers. Some researchers have organized exiting theories and frameworks by level of application (i.e. individual, group, organization, and larger environment)

and generalizability of constructs, while others have used a structured process to consolidate, simplify, and focus on the needs of healthcare implementation science research.

A first method for improving accessibility, by Nilsen, was to define a taxonomy for categorizing theories, models, and frameworks around the objectives of implementation research, namely (1) translate research into practice (process models); (2) understand and/or explain implementation outcomes (determinant frameworks, classic theories, implementation theories), and (3) evaluate implementation interventions (evaluation frameworks).[49] Many of the models proposed in the evaluation by Nilsen have their origins in nursing research.

A second attempt to improve accessibility has been through consolidating and simplifying theories, models, and frameworks to create pragmatic tools for implementation researchers. Michie et al.[50] collaborated with a group of theorists with expertise in the fields of health psychology and health services research, to identify 33 relevant psychological theories. The teams consolidated the constructs from these theories and prioritized those with the most relevance to healthcare implementation science research. Overall, a subset of the 128 constructs were identified as important for behavioral change in the healthcare setting. Examples include (1) reinforcements and rewards, (2) perceived control/self-efficacy, (3) intention, (4) action planning/implementation intention, (5) outcome expectancy, (6) goal setting/self-monitoring, (7) environmental triggers, (8) organizational culture/context, (9) punishment, (10) behavioral control (barriers and facilitators), (11) motivation, (12) attitudes, (13) morale, and (14) habit/routines. The resulting product was a guide, organized by domain and construct, which researchers can reference for developing interview questions for studying the implementation of evidence into practice. To aid understanding of this approach, a partial list of the domains, constructs and example interview questions are listed in figure two (below).

A third effort at consolidating theories was the development of the Consolidated Framework for Implementation Research (CFIR), which was created out of research for the Veterans Affairs Diabetes Quality Enhancement Research Initiative (QUERI).[51] To create this framework, Damschroder et al. conducted a literature review of theories, models, and frameworks that facilitate the implementation of evidence into practice in the healthcare sector. This framework includes five domains, including intervention characteristics, outer setting, inner setting, characteristics of individuals, and process, with several constructs within each domain. This work has been used extensively in implementation evaluation studies and has been cited in over 800 research articles. This framework was used to inform the creation of the interview guides for aim two of this study.

A fourth approach for making implementation theories more accessible is to organize theories and frameworks by level and/or discipline. Tabak et al. developed an inventory of theories and frameworks related to implementation science and organized each by level, field of origin, and flexibility.[52] Construct flexibility was ranked on a scale of 1-5, where one was assigned if the construct had a broad applicability to a variety of implementation activities and five was assigned if the construct was narrowly focused on a particular set of activities (e.g. Dearing et al. and their Convergent Diffusion and Social Marketing Approach for Dissemination, which focused on public health and physical activity). The authors also included a list of studies

Figure 2: Theoretical domains, component constructs, and questions for investigating the implementation of evidence into practice [50]

(6) Motivation and goals (Intention)	Intention; stability of intention/certainty of intention Goals (autonomous, controlled) Goal target/setting Goal priority Intrinsic motivation Commitment Distal and proximal goals Transtheoretical model and stages of change	How much do they want to do *x*? How much do they feel they need to do *x*? Are there other things they want to do or achieve that might interfere with *x*? Does the guideline conflict with others? Are there incentives to do *x*?
(7) Memory, attention and decision processes	Memory Attention Attention control Decision making	Is *x* something they usually do? Will they think to do *x*? How much attention will they have to pay to do *x*? Will they remember to do x? How? Might they decide not to do x? Why? (prompt: competing tasks, time constraints)
(8) Environmental context and resources (Environmental constraints)	Resources/material resources (availability and management) Environmental stressors Person × environment interaction Knowledge of task environment	To what extent do physical or resource factors facilitate or hinder *x*? Are there competing tasks and time constraints? Are the necessary resources available to those expected to undertake *x*?
(9) Social influences (Norms)	Social support Social/group norms Organisational development Leadership Team working Group conformity Organisational climate/culture Social pressure Power/hierarchy Professional boundaries/roles Management commitment Supervision Inter-group conflict Champions Social comparisons Identity; group/social identity Organisational commitment/alienation	To what extent do social influences facilitate or hinder *x*? (prompts: peers, managers, other professional groups, patients, relatives) Will they observe others doing *x* (i.e. have role models)?

that have used the theory. Estabrooks et al. organized models by discipline and activity, including nursing, health promotion, organizational and social sciences.[53] Models are listed according to level of impact; details for this are beyond the scope of this review.

The **nursing literature** alone contains a robust body of theoretical models and frameworks directly applicable to implementation science. Examples of models and frameworks that have achieved international recognition and have been cited extensively in the literature include the Knowledge to Action Cycle by Graham et al.[54], Promoting Action on Research Implementation in Health Services (PARIHS) framework by Kitson, Harvey, and McCormack;[55] Ottawa Model of Research Use;[56] Iowa model of evidence-based practice[57], and Dissemination and Use of Research Evidence for Policy and Practice Framework. An analysis by Mitchell et al. grouped models into the following four areas: (1) evidence transformation processes; (2) strategic

change to promote adoption; (3) knowledge exchange and synthesis for application; and (4) designing and interpreting dissemination research. The authors identified models by Dobbins[58], Kitson, Harvey, and McCormack[55], and Stetler [59] as particularly useful and practical when designing interventions.

The preceding sections provided a limited overview of the theoretical inventory for implementations science and attempts to improve accessibility. A criticism in this field is that the sheer volume of theories and frameworks may actually complicate theory selection and result in a lower utilization in study design.[41] Indeed, a review of the literature found that few studies of implementation actually utilize theory: only 22% of rigorous evaluations of clinical practice guideline implementation studies provided a theoretical rationale for interventions.[60] In this review, three theories were used in more than half of these studies. The PRECEDE, Diffusion of Innovation, and Information Overload theories were referenced the most; however, few studies provided rationale for theory selection. The lack of theoretical foundation for these studies makes it difficult to identify the mechanisms through which these interventions have had their effect.

Implementation science intervention types and outcomes. There are a wide range of interventions for promoting the uptake of evidence into practice, but effectiveness ranges considerably for each type. Interventions can be organized using the Cochrane Effective Practice and Organization of Care (EPOC) taxonomy of health systems interventions for categorizing interventions (Figure 3) and can be further categorized into passive (e.g. distribution of educational materials) and active strategies.[38]

Figure 3: EPOC Taxonomy for Implementation Interventions[38]

- **Distribution of educational materials**: distribution of published or printed recommendations for clinical care, including clinical practice guidelines, audiovisual materials and electronic publications. The materials may have been delivered personally or through mass mailings.
- **Educational meetings**: healthcare providers who have participated in conferences, lectures, workshops or traineeships.
- **Local consensus processes**: inclusion of participating providers in discussion to ensure that they agreed that the chosen clinical problem was important and the approach to managing the problem was appropriate.
- **Educational outreach visits**: use of a trained person who met with providers in their practice settings to give information with the intent of changing the provider's practice. The information given may have included feedback on the performance of the provider(s).
- **Local opinion leaders**: use of providers nominated by their colleagues as 'educationally influential'. The investigators must have explicitly stated that their colleagues identified the opinion leaders.
- **Patient-mediated interventions**: new clinical information (not previously available) collected directly from patients and given to the provider, e.g. depression scores from an instrument.
- **Audit and feedback**: any summary of clinical performance of healthcare over a specified period. The summary may also have included recommendations for clinical action. The information may have been obtained from medical records, computerised databases or observations from patients.
  The following interventions are excluded:
  - provision of new clinical information not directly reflecting provider performance which was collected from patients, e.g. scores on a depression instrument, abnormal test results. These interventions should be described as patient mediated
  - feedback of individual patients' health record information in an alternative format (e.g. computerised). These interventions should be described as organisational.
- **Reminders**: patient- or encounter-specific information, provided verbally, on paper or on a computer screen, which is designed or intended to prompt a health professional to recall information. This would usually be encountered through their general education, in the medical records or through interactions with peers, and so remind them to perform or avoid some action to aid individual patient care. Computer-aided decision support and drugs dosage are included.
- **Marketing**: use of personal interviewing, group discussion ('focus groups'), or a survey of targeted providers to identify barriers to change and subsequent design of an intervention that addresses identified barriers.
- **Mass media**: (1) varied use of communication that reached great numbers of people including television, radio, newspapers, posters, leaflets and booklets, alone or in conjunction with other interventions; (2) targeted at the population level.
- **Other**: other categories to be agreed in consultation with the EPOC editorial team.

A review of the evidence related to implementation science interventions showed that interventions using active strategies are more likely to be successful.[38,61] Most interventions identified in the literature addressed one level (i.e. individuals/healthcare providers). While evidence shows that single interventions produce some effect on provider behavior, it is not clear if these changes persist in the long-term. Methods most commonly evaluated in the literature include (1) reminders, (2) provision of education, and (3) audit and feedback. Note that interventions related to electronic reminders have since become more advanced to include a wider range of designs, including CDSSs. Section 2 provides an overview of the different classes of

CDSSs. The majority of interventions presented in the literature have been targeted at physicians. Evidence shows positive impacts on physician outcomes (e.g. changes in provider behavior), but the strength of the evidence is less robust for impacts related to nursing practice.

A review of the literature shows that some implementation science interventions are more effective than others. A large systematic review of strategies for implementing clinical practice guidelines, sponsored by the National Health Service Health Technology Assessment Program, assessed 235 studies, which included both controlled trials (65%) and quasi-experimental studies of single and multiple interventions.[38] The majority of studies were conducted in the USA and approximately 20% of studies were conducted in the inpatient setting. Most interventions targeted physicians (75%), with most targeting a single medical specialty only. The most commonly tested strategies for single intervention studies were (1) provider reminders, (2) provision of educational materials, and (3) audit and feedback. Most multifaceted interventions included educational outreach. Results for performance improvements (median absolute) across interventions were 14% for reminders (14 cluster randomized comparisons), 8% for educational materials (four cluster randomized comparisons), 7% for audit and feedback (five cluster randomized comparisons), and 6% for multi-faceted interventions that included educational outreach (13 cluster randomized comparisons). The authors found no significant association between number of interventions tested in a study and effect on outcomes.

A more recent 2011 summary of the effectiveness of provider behavior change strategies from EPOC systematic reviews found somewhat different results.[62] In this latest summary, the most commonly tested strategies included (1) audit and feedback; (2) educational meetings; and (3) educational outreach. Effect sizes for the these interventions were as follows: (1) audit and feedback - 5.0% median absolute improvement in care (interquartile range +3.0% to +11.0%); (2) educational meetings - 6.0% median absolute improvement in care (interquartile range +1.8% to 15.3%); (3) educational outreach - 4.8% median absolute improvement in prescribing behavior

(interquartile range +3.0% to + 6.5%) and a 6.0% median absolute improvement in other provider behavior, such as provision of smoking cessation counseling and reducing inappropriate antibiotic prescribing behavior. Previous reviews combined both computerized and non-computerized reminders. Results of a systematic review of the effects of **computerized reminders** only on process of care outcomes showed more modest effects on provider behavior.[63] Overall median absolute improvement on process of care outcomes was approximately 4.0%. Inpatient impacts of this intervention were greater than outpatient: 8.7% (IQR: 2.7% to 22.7%) versus 3.0% (0.6% to 11.5%). Reminder interventions that required users to enter a response in order to proceed had a larger impact on process adherence outcomes (approximately 12.0% versus approximately 3.0%).

It is important to note that, while implementation science interventions have been studied extensively for physicians, the **evidence base for nursing practice is still growing**. Most studies that have focused on nurses have evaluated the impact of educational interventions. Overall, the quality of the evidence base is still low. Three reviews of the literature have been conducted in the past two decades. A selective review by Closs and Cheater in 1997 found primarily descriptive accounts regarding the impact of implementation strategies and their effectiveness.[61] Strategies included audit and feedback and educational interventions. Studies reported positive impacts on both processes of care and patient outcomes. Multi-faceted interventions were also reported, which included combinations of various types of educational strategies such as in-service education, small group teaching, and provision of educational material, research articles, and posters. Opinion leader interventions were used to a lesser extent. Overall, the authors reported that it was not possible to draw any conclusions regarding the effectiveness of different implementation in nursing. A systematic review by Thomas in 1999 found only three studies that evaluated the impact of implementation interventions.[64] Two of these studies tested interventions on nurse-practitioners and physicians, but did not report outcomes by role. The third study focused on the implementation of evidence-based practice interventions on nurses. Provider

improvements were seen in groups that received guidelines + in-service lectures + opinion leaders and those that received guidelines + opinion leaders compared to those who only received guidelines + in-service lectures; however, no statistical results were provided. A review by Thompson et al. in 2007 found a limited number of studies, most of which were educational interventions.[65] The authors concluded that there was insufficient evidence to support the use of educational meetings for increasing research use among nurses. The author's search yielded three randomized control trials and one controlled before- and after-study, with only one study from the USA.

Since these three literature reviews, a number of studies have been conducted in the acute care setting in the USA to evaluate the effect of implementation interventions on nurse behavior;[66–72] however, the overall quality of the evidence is low. Evidence presented in these studies was rated low for four key reasons: (1) lack of control groups in intervention design; (2) poor reporting of statistical analysis, (3) lack of adjustment for covariates in analysis, and (4) poor reporting/lack of information regarding outcomes. All studies included an educational intervention. Most studies were multifaceted, with most including both meeting and educational material interventions. All studies used a quasi-experimental design. Given the diversity of the nursing workforce in terms of education, specializations, and work settings, interventions that are successful with physicians may not be as successful with nurses. Therefore, understanding the impact of implementation science interventions on nursing practice is an important area for future inquiry.

Implementation science seeks to improve the systematic uptake of research findings into routine practice to improve the quality and effectiveness of health services and to improve patient outcomes. More research is needed in this field to understand the types interventions that are most suited for different types of evidence and provider type (i.e. nurses and physician/advanced practice nurses). Furthermore, research is needed to understand the impacts of non-education

based interventions, as well as the long-term impacts of interventions on changing provider behavior.

Health information technology in the form of clinical decision support systems (CDSS) has emerged as a promising tool for implementing evidence into practice and in *sustaining practice changes*. The following section provides an introduction to CDSSs and an overview of their impacts on provider outcomes.

Clinical Decision Support Systems

Health information technology, namely the use of electronic health record (EHR) systems, has been viewed as a mechanism to address the myriad challenges faced when providing healthcare services in a complex environment. The general belief is that computerized systems will assist providers in delivering higher quality care to patients through improved efficiencies and better access to key information, which in turn will result in improved patient outcomes.[73,74] The U.S. federal government has spurred significant investment in EHR system adoption through the 2009 Health Information Technology for Economic and Clinical Health Act (HITECH Act). Approximately $26 billion was allocated in federal funds to promote adoption and "meaningful use" of EHR systems, which includes the implementation and meaningful use of CDSSs.[75] The last decade has seen a significant increase in the use of EHR and CDSS functionality. As of 2015, approximately 80% of hospitals had adopted a basic EHR system, compared to approximately 15% in 2010. Hospitals using advanced EHR functionality, such as clinical decision support features, show a similar trend: 40% of hospitals in 2015 reported using CDSS functionality, compared to only 3% in 2010.[76]

CDSS organization: Functionality and content. CDSS types can be organized by functionality (figure four) and by content. The literature contains numerous examples of implementations of each system class in the acute care setting; however, systems that provide

Figure 4: CDSS Functional Classes and Definitions[161]

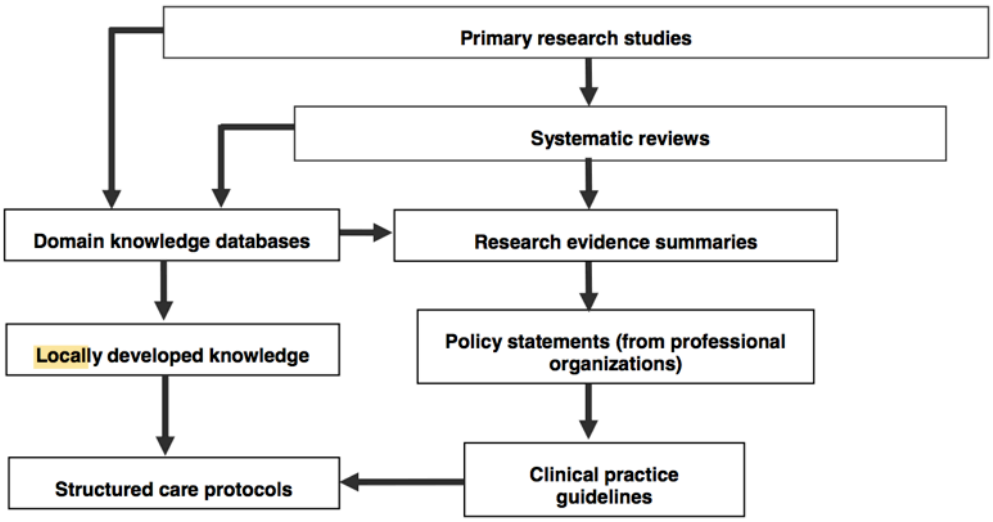
Class	Function
Feedback	Provide feedback by responding to an action taken by the clinician or to new data entered into the system
Data organization	Organization and presentation of disparate data into logical, intuitive schemas at the point-of-need
Proactive information	Provision of information to the clinician at the point-of-need (eg, clinical pathway on pneumonia when patient with pneumonia is being admitted to hospital)
Intelligent actions	Automation of routine and repeated tasks for the clinician on a regular time schedule (eg, provision of all new laboratory values on current patient list every morning)
Communication	Alert clinician and other providers who need to know about unusual data (eg, test results) or communications regarding specific patients
Expert advice	Diagnostic and therapeutic advice using a comprehensive knowledge base and a problem-solving method, such as probabilistic reasoning, neural nets, or heuristic rules

feedback to providers in the form of alerts, reminders, and recommendations are currently the most common class[77], which is likely the result of the HITECH financial incentives to hospitals for CDSS adoption. Feedback systems have been implemented in multiple healthcare professional domains including nursing, pharmacy, and medicine.[78]

System content can be organized into two types: (1) Non-knowledge based and (2) Knowledge based.[79] Non-knowledge based systems include systems that employ automated learning techniques that use computers to identify patterns and generate information. Knowledge based systems are built upon knowledge generated from primary research studies. Figure five

contains the hierarchy of research evidence, in increasing order of synthesis, used to generate content for CDSSs. Lobach et al. added three additional sources of knowledge, namely (1) domain knowledge databases (domain specific knowledge such as drug formularies), (2) locally developed knowledge (evidence derived from the specific context of care that is specific to the local setting), and (3) structured care protocols (setting specific adaptations of clinical practice guidelines, such as knowledge derived from local expert panels or from data analysis of setting specific data).[4] Knowledge-based CDSSs incorporate the aforementioned sources of knowledge with patient specific data to provide decision support to users.

Figure 5: Types of Knowledge used in CDSSs[4]



CDSS focus and target areas of care. CDSS can aid healthcare providers at various phases within the care delivery process, with different classes of systems used at various points in the care delivery. Areas of care where CDSSs have been implemented include preventative care, diagnosis, treatment planning and implementation (including medication preparation and administration), care follow-up as well as chronic disease management. In general, most CDSSs target single conditions (e.g. cancer pain management, delirium superimposed on dementia for older adults, sepsis alerts for ICU patients). With few exceptions, most CDSSs have focused on

providing decision support to physicians and advanced practice nurses.[77,80,81]

Theoretical foundations. Theories, models, and frameworks for explaining user acceptance of health information technology systems is a relatively mature area of information systems research.[82] There are a number of well-known, empirically validated, and highly cited theories and models for supporting this area of research. Notable models include Technology Acceptance Model (TAM)[83], Unified Theory of Acceptance and Use of Technology (UTAUT)[84], which is related to TAM, and the DeLone and McLean (D&M) model for information system success.[85] These models were developed outside of the healthcare context, which is a major criticism to using these for studies related to health information systems. For example, in the TAM and D&M models, the social/group influence, an important consideration in the healthcare context[86], is absent from the model constructs. The UTAUT model was updated to take into account social influence, but fails to capture the complexity related to hierarchical relationships in the acute care setting and the influence of external factors, such as regulation and policy.

Within the healthcare environment, evaluation of technology must be assessed within the complex interplay between organizational culture, group dynamics, individuals, workflow, and system content and design. A model that successfully captures this dynamic is the **Socio-technical Model for Studying Health Information Technology in Complex Adaptive Healthcare Systems**[87] This model captures the basic constructs that are critical to understanding and assessing the effect of technology in the healthcare context and includes external rules and regulations; organizational culture, policies, and procedures; hardware/software; workflow and communication; people; human computer interface; and clinical content.[88] Moreover, this model further breaks down the technology into content and interface, which both can separately influence system use and adoption. What is also unique about this model is that, unlike the TAM or UTAUT models, the relationships between constructs are presented in a non-linear form, thus capturing the dynamic and chaotic nature of the healthcare environment. A second notable

framework is the recent **Health Information Technology Research-based Evaluation Framework (HITREF)** developed by Sockolow, Crawford, and Lehmann.[89] This comprehensive framework, based on an extensive literature review and analysis, addresses factors at multiple levels within the healthcare setting, namely individual, group, organization, and environment. This model also addresses outcomes that are important for health services research, such as cost and patient outcomes (i.e. morbidity, quality of life, and mortality).

CDSS outcomes. CDSS outcome measures can be organized into several large groups. In a large systematic review, Bright et al. used the following six outcome categories: (1) Clinical outcomes; (2) Processes of care (provider adoption or implementation of CDSS recommendations for preventative care or treatment); (3) Workload, Efficiency, and Organization; (4) Patient satisfaction; (5) Cost-effectiveness; (6) and Use and Acceptance.[77] This organizational approach has been used in other studies, namely a large comprehensive systematic review by the Agency for Healthcare Quality and Research (AHRQ).[4] With regards to the process of care (category 2) outcomes, as the adoption of CDSSs increases throughout the healthcare setting (e.g. CDSS to guide provider venous catheter selection), other sub-categories will be required to capture the full breadth of impacts.

Overall, most CDSS studies in the literature have evaluated the impact of these systems on *processes of care* (category two), with most studies reporting a positive impact on this outcome. A large meta-analysis sponsored by the Agency for Healthcare Quality and Research (AHRQ) in 2012 analyzed 148 randomized controlled trials according to their impact on the above outcomes and found that approximately 85% of all studies assessed at least one type of process of care measure. Approximately 20% of these studies evaluated the impact of the CDSS on order or follow-through with treatment recommendations (e.g. test ordering reminders for certain medication orders, diagnosis recommendations) and overall, CDSSs positively impacted adherence to recommended therapies/orders. Most studies for this category were conducted in the

ambulatory setting (83%) and most systems were customized by the organization (70%). A recent integrative review by Lopez et al. of CDSSs used exclusively by nurses in the acute care setting (n=28) found that the majority of studies (randomized controlled trials and quasi-experimental studies) also included at least one process of care outcome (n=22).[80] Most studies reported positive improvements in outcomes, although it is important to note that the authors defined process of care outcomes as, for example, cognitive workload impacts and decision-making efficiency. No study in this review assessed adherence to CDSS recommendations.

Impacts on *provider use and acceptance has been less rigorously evaluated* in the literature. The AHRQ sponsored meta-analysis found that out of the 148 randomized controlled trials included in this analysis, only 24 studies reported the effect of the CDSS on provider acceptance of CDSS. The authors rated the evidence for provider acceptance of a CDSS system as low, also noting that many of the studies had significant limitations such as inconsistent definitions of provider acceptance and small sample sizes. This outcome has been more commonly evaluated using quasi-experiment study designs, which have major internal validity risks due to unobserved variables bias.[90]

CDSS factors associated with system use and acceptance. Barriers to and facilitators of system use exist at multiple levels of an organization. The Socio-Technical Model for Studying Health Information Technology in Complex Adaptive Systems by Sittig and Singh was used to organize the review of factors.[87] Components of this system include (1) people (e.g. providers), (2) CDSS system and interface design, and (3) other contextual factors such as workflow, culture, and organization structures.

(1) Provider factors. It is important to understand how different provider types (e.g. nurses, nurse practitioners and physicians) use CDSSs and factors associated with increased acceptance and use, as this information can inform CDSS strategies to optimize system use across various provider types. Multiple studies have identified provider factors associated with system

acceptance, which was defined previously as provider acceptance of CDSS recommendations. Prescriber type, investments in provider training, and preferences and autonomy were found to be associated with the acceptance of CDSS recommendations.

Measuring CDSS system acceptance has been assessed both quantitatively by studying system overrides, as well as qualitatively. A study by Cho et al. sought to identify provider-level characteristics, one of the few studies to specifically examine nurse practitioners (NP) as well as physicians, and their effect on variation in CDSS recommendation acceptance.[123] Results of this analysis found that system alert override rates (defined as non-acceptance to CDSS recommendations) for NPs were significantly lower than physician groups (.23 vs .44, p-value <0.00001). Type of physician, such as house staff (i.e. residents and interns), were also found to be associated with override rates. House staff were found to override alerts less often than staff physicians. This difference was noted even when age was taken into account: within each age group, house staff overrode alerts less often than did staff physicians. A large systematic review by Moxey et al., which included all study designs (randomized controlled trials as well as qualitative studies), identified inadequate investment in provider training as a key barrier to provider system acceptance.[91] Additionally, CDSS as a threat to professional autonomy and the fear that use of CDSSs for decision support may lead to an overreliance on technology were also identified as barriers in this analysis. However, in contrast, other studies found that providers had a more favorable view of CDSSs, believing that they improved decision-making. This analysis did not provide information on the context and culture of the organization, which are necessary to understand how and why providers might have such contrasting views of CDSS.

(2) CDSS design factors. Authors have taken multiple approaches to identifying system features associated with use and acceptance, including (1) systematic review and meta-analysis of studies of CDSS systems, (2) predictive modeling, and (3) studies of different methods for information presentation. The systematic reviews and meta-analyses yielded a list of design

features and organization and process considerations, whereas approaches two and three yielded information about the presentation of the content of these systems.

Three large, high quality meta-analysis identified approximately 13 features related to increased system success. Kawamoto et al. performed a meta-analysis in 2005 of 70 randomized control trial studies and identified 13 factors related to success (figure six).[92] A large meta-analysis sponsored by the Agency for Healthcare Quality and Research (AHRQ) in 2012, which included results from Kawamoto el al., analyzed success factors by *outcome category* and found two consistent themes across studies that evaluated the impact of CDSSs on provider use, namely (1) provision of decision support at the time and *location* of decision-making and to the right person and (2) provision of an actionable recommendations.[4] A third major meta-analysis was conducted in 2013 by Roshanov et al.[93]. The authors contacted study authors to gather additional data related to system features and found similar results to the previous two studies. However, the authors added a new feature related to system evaluation and development and found higher odds of system success if the evaluation was also conducted by the system developer.

How content is displayed to the user is just as important for system acceptance as process and system design considerations. Seidling et al. used a novel approach to identifying system features associated with system acceptance or use.[88] Hypothesizing that system acceptance is modulated by decision support content (quality of information) and information presentation, the authors sought to empirically evaluate the relationship between these factors and acceptance of CDSS feedback systems (i.e. alert systems). Using multivariate prediction models of CDSS recommendation override logs from multiple CDSSs used within multiple hospitals, the authors found that display of decision support information (e.g. visibility, legibility, color, proximity to action, summary of information on the screen) were most strongly associated with acceptance. The implications of this finding are that presentation of information in the user interface is an important factor for decision support acceptance. Additionally, level of detail in the decision

support alert (e.g. detailed guidance) was associated with increased likelihood of acceptance.

Figure 6: CDSS Features Related to System Success

1. **General System Features**
    a. Integration with charting/order entry (OR 1.47[B])
    b. Computer-based decision support (OR 6.3[A])
    c. Local user involvement in development (OR 1.45[B])
2. **Clinician-System Interactive Features**
    a. Automatic provision of support as part of clinician workflow (OR 12.9[A]; 1.45[B])
    b. Provision at time and location of decision making (OR 15.4[A]; 1.78[B])
    c. Documentation of reason for not following system recommendations (OR 11.23[C])
    d. No need for additional clinician data entry (OR 1.43[B])
    e. Recommendations executed by noting agreement
3. **CDSS Communication Features**
    a. Provision of a recommendation, not just an assessment (OR 1.3[A]; 1.5[B])
    b. Promotion of action rather than inaction (OR 1.28[B])
    c. Justification via provision of research evidence or reasoning
4. **Auxiliary Features**
    a. Provision of support results to both clinician and patient (OR 1.18[B]; 2.77[C])
    b. CDSS accompanied by period performance feedback
    c. CDSS accompanied by conventional education
5. **Evaluation**: CDSS evaluated by developers (OR 4.35[C])

A (Kawamoto et al.); B (Lobach et al.); C (Roshanov et.al) significant in multivariate meta-analysis

A third approach to identifying system functionality and features associated with increased acceptance has been to consider end-user rationality and control. Brenner frames CDSS feature design considerations from the viewpoint of "user control" and "user autonomy" and views these as influential concepts in a user's reaction to CDSS information. The author states that system designs must balance provider autonomy--how much control providers have over how they respond to system decision support recommendations may impact system acceptance and satisfaction.[94] Along this design paradigm, behavioral economic principles have been applied to CDSS design and information presentation in the form of choice architecture. This branch of research posits that provider decision-making (i.e. acceptance of decision support) can be influenced by engineering better decision choices.[95] Several recent studies in healthcare have redesigned CDSS information presentation by incorporating system defaults in medication

ordering to help providers make optimal patient decisions. For example, Bourdeaux et al. created order set templates for resident physicians with medication bundles. Providers could choose to opt out of medications, but they would have to select other medications manually, which was more time consuming. Prescribing rates for this evidenced based medication bundle increased significantly compared to before the intervention.[96] Similar strategies have been applied in other studies with similar outcomes.[32,34]

(*3) Contextual factors.* Contextual factors are key to understanding how different environmental aspects (i.e. culture, organizational structure) impact system use, which is critical to understanding transferability and generalizability of study findings. Overall, multiple systematic reviews found a dearth of information on contextual factors that may affect provider-related outcomes. Overall, contextual factors affecting system use can be grouped around the follow themes: system usability issues, quality of CDSS algorithm, process issues, and safety.

A systematic review of qualitative studies that focused on identifying contextual factors for CDSS use found that high quality evidence for understanding provider experience in using CDSSs is rare and that knowledge about the integration of CDSSs into real world settings is lacking.[97] The search results yielded 47 qualitative evaluations of CDSSs used to support provider (MD, NP, RN) practice; however, most studies had significant issues with dependability and confirmability. Approximately 80% of CDSSs were implemented in outpatient settings, most studies focused on physician experiences only, and most CDSSs were alert- or reminder-based (Class: Feedback – Figure 3). The most common data collection method across all studies was semi-structured interviews, combined with non-participant observation. No study employed established methods used to elicit information regarding human-computer interaction factors, such as contextual design and inquiry methods.[98–100] Two studies investigated evidence of provider (RN) adaptation to CDSS algorithms, but no study evaluated if this was also occurring with other provider types. A large meta-analysis sponsored by the Agency for Healthcare Quality

and Research (AHRQ) also found significant omissions in study descriptions of contextual factors related to system use and adoption.[77] A systematic review of CDSS for multi-morbidity also found a significant lack of human-computer interaction considerations in the studies. [101]

Background for Venous Catheter Selection Guideline Creation

In this study, we use as an exemplar the implementation of an evidence-based clinical decision support system (CDSS) intervention designed to support decision-making for venous catheter device selection. Patient risk for adverse events varies considerably across the spectrum of venous catheter options. Selection of appropriate catheter options is a nuanced process and depends not only on medications to be administered and duration, but also, in some cases, on patient and organizational factors. This section presents an overview of the risks associated with PLCs and MLCs, namely venous thromboembolism (VTE) and blood stream infection risks, to provide the reader with an understanding for the need for decision-making for venous catheter selection.

Venous thromboembolism. PLCs carry the highest risk for VTE, [10,11,102–108] compared to all other venous access devices. VTE encompasses both deep vein thrombosis (DVT) and pulmonary embolism (PE). A recent meta-analysis found that the overall rate for PLC-associated DVT was 4.86% (CI 4.08%-5.64%).[12] However, rates vary significantly by setting, history, catheter lumen diameter and number, and active cancer diagnosis. A systematic review and meta-analysis by Chopra et al. analyzed the frequency of VTE in a large group of studies and found that patients in the intensive care unit (ICU) setting had the highest incidence of VTE, 13.91%, (CI 7.68%-20.14%), followed by patients with cancer diagnosis, 6.67% (CI 4.69%-8.64%). Non-ICU patients had the lowest frequency at 3.44% (CI 2.46%-4.43%). In a randomized controlled trial to compare PLCs to other *peripheral* intravenous devices, PLCs were associated with a 6.6 relative-risk of DVT. [103]

MLCs have been shown to have a much lower rate of VTE and blood stream infections compared to PLCs. Evidence shows that MLCs have a bloodstream infection rate of 0.4%.[7]

VTE is a serious complication and can have both immediate and long-term adverse health outcomes for patients. Symptoms for VTE range from mild to debilitating and can include edema and pain in the affected locations for DVT and chest pain, shortness of breath, and rapid heart rate for PE. [109] Thirty-day mortality estimates for VTE range between 10%-30%.[18,19] Risk for recurrent VTE are high,[110] with approximately 7%-14% experiencing a recurrent event within one year [19,111] and 30% within 10 years.[112,113] Furthermore, 30-day readmissions rates for patients with DVT and PE are approximately 23% and 33%, respectively.[20] Cost estimates for treatment of acute DVT are $12,000 to $15,000, with subsequent complications costing $18,000-$23,000.[114] VTE adds an estimated 4.6 days to a patient's hospital length of stay.[10] Patients can experience anxiety and trauma as a result of medical treatment for VTE. Initial treatment may include anticoagulant medications and thrombolytic therapy[115], with most patients requiring long-term treatment.[115] As anticoagulant medications can have serious side effects, such as bleeding, patients must take medications exactly as directed, which has further implications for patients who lack practical support for obtaining medications or adhering to medication regimens.[116]

Bloodstream infection. Central line associated blood stream infections (CLABSI) risks associated with PLCs used in the acute care setting are similar to other CVC types, but may *vary by setting and patient and catheter characteristics*.[117] A large retrospective cohort study found rates as high as 6%, resulting in an infection rate of 2.16 per 1000 catheter-days.[13] Risk factors for **PLC-associated CLABSI** include: stay in an intensive care unit, multiple PLC lumens, as well as a longer length of hospital stay. [13] A prospective study found that after adjusting for patient and provider factors, patients in intensive care units had slightly higher odds of developing CLABSI and had an earlier time to infection as well (Odds Ratio 1.02; CI 1.01-1.03; P<.0001 and Hazard Ratio 1.02; CI 1.01-1.02; P<.0001).[117] Number of lumens is strongly associated with PLC-

associated CLABSI. One study found that patients with triple lumen PLCs had an over 6-fold increase risk of CLABSI (Odds Ratio 6.34; CI 1.85-21.71; P=.003). Furthermore, **multiple lumens were also associated with earlier time to infection** (HR 8.52; CI 2.55-28.49; P=.0003).[117] A retrospective longitudinal study conducted with ICU patients found that catheter dwell time and patient co-morbidities were associated with higher risk of PLC-associated CLABSI, compared to other catheter types.[118] Risks for **midline-associated blood stream infections** are negligible and are on par with other types of peripheral intravenous devices.[119]

While PLCs have numerous benefits for providing medical treatment, evidence suggests a possible overuse and inappropriate use of PLCs and a **lack of understanding about indications and risk by providers**.[24] A large survey conducted in 10 hospitals in Michigan across five healthcare systems showed a widespread misunderstanding of the appropriate usage for PLCS and the risk for complications, such as VTE and CLABSI. [120] The results showed that practitioners believed that PLCs were the safest of the central venous catheter options and that they did not understand appropriate indications for PLC usage.

Study Contributions

A large number of studies have evaluated the impact of CDSS on outcomes and many studies have found a positive impact; however, gaps remain in the literature. This study will add to the literature in a number of key ways.

1. **Diverse user types:** There is currently a gap in the literature about how the characteristics of users are associated with usage of CDSSs.[4] This tool is used by multiple provider types, from advanced practice nurses to physician interns, residents, and hospitalists.
2. **Novel domain**: To our knowledge, this study will be the first to evaluate a CDSS designed to assist providers in selecting between *multiple* vascular access devices for

patients in the acute care setting.

3. **Hospital-wide implementation of a clinical practice guideline based CDSS**: The Vascular Access CDSS, a clinical practice guideline based intervention, was implemented throughout all acute care units and is used by all specialties. Most evaluations of guideline based CDSSs published in the literature have focused on a specific specialty (e.g. radiology and use of imaging; asthma care in pediatrics), thus this study will add evidence regarding the use of a hospital-wide CDSS system.[4]
4. **Generalizable solution:** This study will evaluate a solution that has been created using commercial, off-the-shelf functionality within an electronic medical record system. Using a *non-customized* solution to present evidence-based recommendations to providers can facilitate implementation of a similar solution in other settings.

CHAPTER 3: STUDY DESIGN AND METHODS

Background

The University of Pennsylvania Health System (UPHS) implemented an evidence based CDSS that assists providers in selecting between PLCs and MLCs. UPHS focused on this particular decision point specifically since (1) there was concern about potential overuse of PLCs and (2) MLCs carry lower risk for adverse outcomes compared to PLCs, yet can be used for many of the same indications as PLCs. This quasi-experimental, multi-method study assessed the effect of the vascular catheter CDSS intervention on provider ordering behavior. Additionally, we identified individual and system level factors that affect provider acceptance elicited information regarding the impact of this intervention on inter-professional communication. The following sections provide information regarding the conceptual models used to guide this study, as well as the design and approach.

Venous Catheter Ordering Process Overview. The following section provides an overview of the roles involved in order creation and review, as well as the systems in place to facilitate workflow (see Appendix A for a diagram of the ordering process). Ordering the placement of a PLC or MLC is a multi-step process involving providers (physicians and advanced practice nurses) and a nurse-led vascular access team (VAT). The nurse-led VAT, established in 2007, is responsible for reviewing and approving all PLC and MLC orders and the subsequent placement. In November of 2013, UPHS implemented a CDSS intervention designed to assist providers (physicians and advanced practice nurses) in the appropriate selection of PLCs and MLCs. This CDSS intervention was linked to an order set within the computerized provider order entry module in a commercial EHR (Sunrise Clinical Manager 5.0, Allscripts, Chicago, IL) used by the University of Pennsylvania Health System. The development and implementation of this intervention was a multi-disciplinary effort and included physicians, nurses, home care, quality specialists, informatics analysts, and nursing infusion experts. A second version of the CDSS interface was implemented in August 2014. See appendix B for interface and list of features included in each CDSS version.

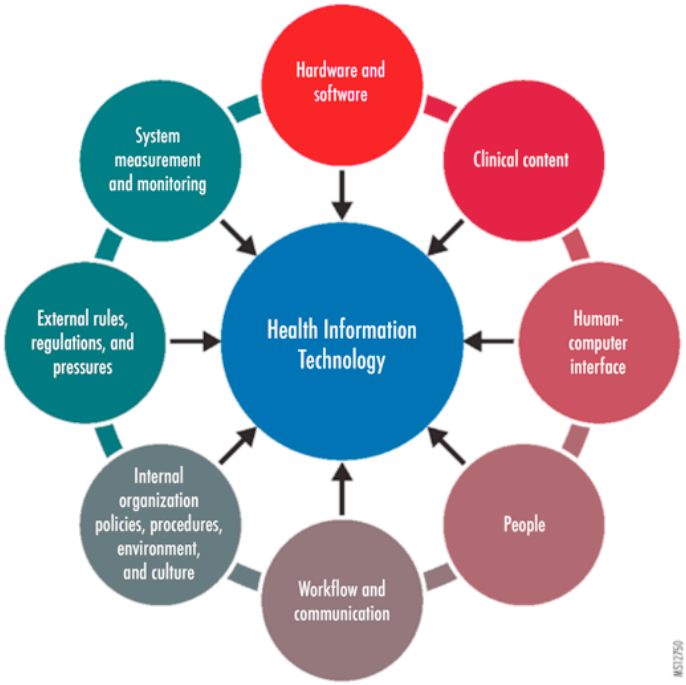
When ordering a venous catheter, providers would navigate to the CDSS by entering the keywords “PICC” or “Midline” into the computerized provider order entry module in the EHR. This was the only mechanism for ordering PLCs or MLCs. Providers entered key patient data (i.e. medication type, duration of intravenous therapy, home care requirements post discharge, associated conditions, and diagnosis). The CDSS would display patient data from the EHR (i.e. creatinine clearance values) on the order entry screen. Upon entry of all required data by the provider, using a computer algorithm based on locally developed evidence-based clinical practice guidelines, the CDSS would present a single recommendation along with rationale to providers. By default, the system will also place a check next to the order type that was recommended by the system. Providers could either accept the recommendation by clicking the “ok” button, or override the recommendation by clicking on a different order type. Once orders are placed by providers, the vascular access nursing team receives a paper based notification (i.e. an order requisition will print to the vascular access nursing office). A VAT nurse will then begin the order review and approval process. The VAT nurse will contact the ordering provider for each catheter placement order to verify information and discuss placement timing. For catheter requests that do not adhere to established evidence-based recommendations, the VAT nurse will discontinue the order and instruct the provider to create a new order following the CDSS recommendations and VAT recommendations.

Note, all data generated from this process (i.e. order creation data, including dates, order status, catheter type; CDSS recommendations; all associated provider and patient data) are stored in a database for each order.

Conceptual Model and Framework

Conceptual model. In this study, a Socio-Technical Model for Studying Health Information Technology in Complex Adaptive Healthcare Systems (STM) by Sittig and Singh [87] (figure seven) was used to evaluate the impact of the CDSS on provider ordering behavior (aim one), as well as to identify factors related to provider acceptance and the impact on inter-professional communication (aim two). This model was selected for this study due to the ability to support the analysis of both qualitative and quantitative aims and due to its extensive use in studies on health information technology.

Figure 7: Socio-Technical Model for Studying Health Information Technology in Complex Adaptive Systems.[87] Adapted from Sittig & Singh, 2010.



In aim one, to assess the impact of the CDSS on provider ordering, the STM was used to guide identification of independent variables. As the decision process for catheter selection is solely dependent on provider/service norms and preferences and patient level factors, including

diagnosis, medication type and duration, and post-acute care planning, we focused on the **People** construct of this model.

In aim two, multiple STM module constructs were used to assess the impact of the CDSS on professional practice and inter-professional communication. The following constructs were selected to guide participant interview instrument development with the objective of identifying how the CDSS impacted clinical practice and inter-professional communication:

A. **Human-computer interface,** to assess how users interacted with the system (e.g. data entered into the system, how users incorporated CDSS recommendations into their clinical practice)
B. **Workflow and communication**, to understand end-user workflow and how the CDSS supported processes and impacted communication within this process
C. **People or personnel**, to identify the different staffing groups that used the CDSS and understand how different groups used the system
D. **Clinical content**, to understand the clinical content of the CDSS (e.g. rules, text) and how this content affected professional practice and decision-making
E. **Internal organization,** to understand how internal procedures, group structure, and specialty culture affected use of the system;
F. **External rules and regulations**, to identify external factors that may have affected clinical practice as it refers to venous access catheter decision-making

Aim two framework. The Consolidated Framework for Implementation Science (CFIR) was used in the development of interview questions for aim two. CFIR, developed by Damschroder et al.[159], was based on a literature review of theories, models, and frameworks that facilitate the implementation of evidence into practice in the healthcare sector. The authors developed a set of qualitative semi-structure interview questions, organized by construct, that can be used to inform study interview guide development.[160] Using the components identified in the

STM referenced above (A-F)[87], questions from related CFIR constructs were modified to fit the aims of this study (See Appendix C for details).

Aim One: Approach and Study Design

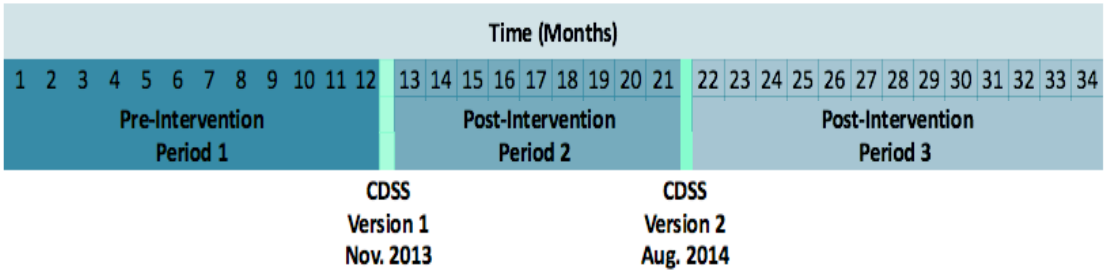
Aim one: aims and hypotheses. The purpose of this aim was to evaluate the effect of the vascular catheter selection CDSS on **provider ordering behavior**. This aim was assessed using the outcomes outlined below:

1. **Proportion of PLC orders**
    - Hypothesis: Proportion of PLC orders out of all catheter orders will decrease post-implementation of the CDSS intervention.
2. **Proportion of discontinued PLC orders**
    - Hypothesis: Proportion of discontinued PLC orders out of all PLC orders will decrease due to the availability of evidence-based recommendations closer to the point of care. Evidence has shown that adherence to CDSS recommendations is higher when information is presented closer to the point of decision-making.[4]
3. **Proportion of double lumen PLC orders**
    - Hypothesis: Proportion of double-lumen PLC orders out of all PLC orders will decrease post-implementation period. Default options have been well documented in the literature as an effective strategy for behavioral change.[32–34]
4. **CDSS-provider order concordance** *(applicable to post-intervention period only)*
    - Hypothesis: Order concordance will increase over time. Evidence has shown that the provision of decision support within the clinical workflow, at the time of decision making, improves adherence to CDSS recommendations.[4,92]
5. **Exploratory aims**: Examine 1.1-1.4 by provider type and service

- Hypothesis: There will be a difference in ordering patterns by provider type and service.

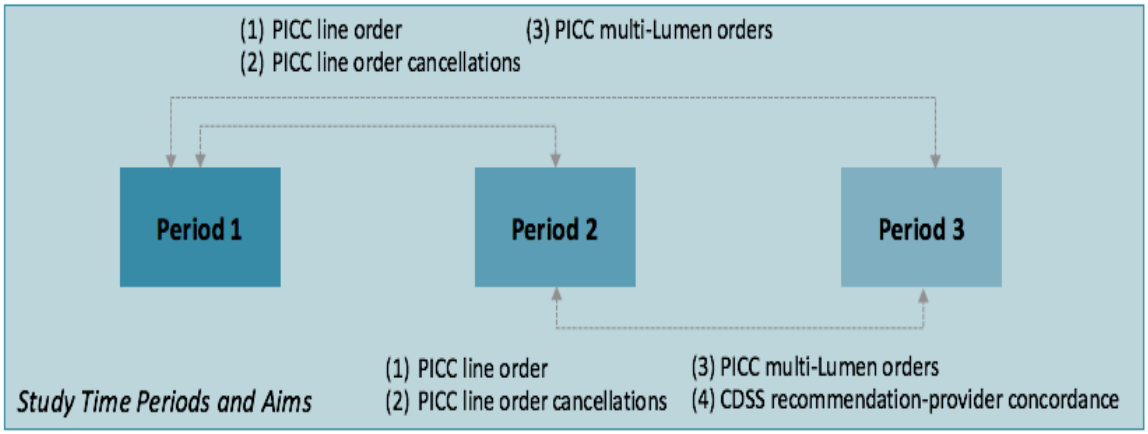
Aim one: approach and study design. For this quasi-experimental study, we conducted a retrospective secondary data analysis of data from the Hospital of the University of Pennsylvania (HUP). Figure eight shows a diagram of the study dates and periods. **Version one** of the CDSS intervention was implemented on November 11, 2013 across all units in HUP simultaneously. Version one contained fields for collecting relevant patient information (i.e. medication type and duration) and a field for indicating the required number of device lumens (single lumen or double-lumen). Additionally, given the strong evidence for greater adverse outcomes for double-lumen PLCs compared to single lumen,[13,29–31] the CDSS designers chose to implement the lumen requirement field using a check box (defaulted to single lumen PLCs for most patient care scenarios). The use of default options has been well documented in the literature as an effective strategy for behavioral change.[32–34] **Version two** of the CDSS was implemented nine-months after version one, on August 26, 2014, across all units simultaneously. In this version, creatinine clearance data, information that is central to decision making, was displayed in the order set. Finally, an additional field was added ("home care"; manual data entry) for providers to indicate whether the patient would be receiving home care services. This field is used by the vascular access placement team for scheduling and prioritization of catheter orders.

Figure 8: Intervention implementation and study time periods



The impact of the CDSS on **provider ordering behavior** was assessed in two ways: comparing outcome measures before and after intervention and between the periods of time after the release of version one and two and post version two (see figure nine). Descriptive analysis as well as multivariate regression models with random effects at the provider level were used to assess the impact of the CDSS on provider ordering behavior.

Figure 9: Outcome measures will be compared between study time periods



Aim one: sample and source. Data generated at the Hospital of the University of Pennsylvania (HUP) were used for this study. The sample included data for all adults, aged 18 years old and older, and admitted to the Hospital of the University of Pennsylvania between November 1, 2012 through August 31, 2015 with a venous catheter order. Twelve months of pre-intervention data (study-period one), November 1, 2012 to November 10, 2013, was used for pre-intervention analysis and served as a comparator for the post-intervention analysis. Twenty-one months of data was used for post-intervention data analysis (November 11, 2013-August 26, 2014 for study-period two; August 27, 2014-August 31, 2015 for study-period three).

Data was obtained from the University of Pennsylvania Health System data warehouse, known as the Penn Data Store (PDS), and the other health system administrative databases. PDS

is a clinical data warehouse consisting of data pooled from multiple electronic medical record platforms used throughout UPHS, and from Horizon Performance Manager, which includes administrative data coded from the medical records.

Aim one: independent variables. Independent variables outlined below were selected due to their potential to influence catheter type decision-making and were based on clinical experience, prior literature, and face validity according to clinical experts. **Patient level** factors, included patient acuity, diagnosis, unit, number and type of intravenous medications, patient demographics, and discharge disposition.[14,98] Patient acuity was modeled using All Patient Refined Diagnosis Related Group (APR-DRG) data[121], as this variable has been shown to be associated with likelihood of having a venous catheter.[122] Provider level factors included specialty and type (e.g. advanced practice nurse, physician). Provider type data was included since evidence suggests that CDSS use may be associated with provider characteristics.[123]

Aim one: analytic strategy. Stata 14.2 (StataCorp LP, College Station, TX) was used for all analysis. The analytic strategy consisted of the following steps.

1. Descriptive statistics of study variables, including means, standard deviations, medians, and interquartile ranges (continuous variables), and frequency counts and percentages (categorical variables). Descriptive statistics were calculated for the overall population and for patients for whom a PLC order was placed. Trends over time and differences between these two populations were examined; this information was used to place subsequent results in context.
2. Analysis of ordering trends over time:
    a. **Data transformation and outcome operationalization:** PLC and MLC detailed order data was collapsed to the month and period level; outcome variables were operationalized as follows:

        (1) Proportion of PLC orders per study-month: Number of PLC orders/PLC +

MLC orders, per study-month

(2) Proportion of discontinued PLC orders per study-month: Number of discontinued PLC orders/PLC orders, per study-month

(3) Proportion of double lumen PLC orders per study-month: Number of double lumen PLC orders/PLC orders, per study-month

(4) Percentage MLC concordance: Number of MLC orders, given a recommendation for MLC order/Total MLC recommended orders, per study-month (see Appendix D for details on the construction of the MLC concordance variable)

b. **Segmented linear regression** models were created for (1) – (3) to assess the statistical significance of changes in the level and slope of the regression lines before and after the introduction of the CDSS intervention.[124] Note that it was not informative to conduct this analysis on outcome (4) concordance as there was no pre-intervention period to use as comparison (the order set in the pre-intervention period did not provide any decision support). The segmented linear regression models allowed us to assess, in statistical terms, how the CDSS intervention affected the outcomes of interest across the three study periods. An unadjusted linear regression model was created, with the outcome of interest and time (study-month and period). Time data was re-centered on study-month 12, which was the month in which the CDSS was introduced. Outcomes were treated as continuous variables.

$$y_{ijkl,m} = \beta_0 + \beta_1 x_{i,m} + \beta_2 x_{j,m} + \beta_3 x_{k,m} + \beta_4 x_{l,m}$$

here $\boldsymbol{i}$ is the preintervention period, $\boldsymbol{j}$ is the postintervention period,

$\boldsymbol{k}$ is the preintervention month, $\boldsymbol{l}$ is the postintervention month,

$\boldsymbol{m}$ is the study month .

$\boldsymbol{\beta_1}$ and $\boldsymbol{\beta_2}$ are the outcome proportion estimates in the pre and post intervention periods

$\boldsymbol{\beta_3}$ and $\boldsymbol{\beta_4}$ are the slope of the lines in the pre and post intervention periods

July effect: a dummy variable was added to these models to understand the impact of trainee changeover during the period of July and August.[125]

c. **Data visualization:** We constructed plots of the raw data for outcomes (1) - (4) over time to visualize the unadjusted impact of the CDSS over time. Predicted values based on the unadjusted segmented linear regression model for outcomes (1) - (3) were also included in the plots.

3. Analysis with variance component models: we hypothesized that PLC and MLC orders created by individual providers would be more correlated, thus we created linear regression models with random intercepts to account for dependence and correlation of provider clustered data.[126] We first analyzed data without covariates and then with covariates of interest. Analysis was done using two datasets: (1) a full orders dataset, which included data for all providers, (2) a subset of the orders dataset in which data was limited to providers who had entered orders in both the pre-intervention and post-intervention periods.

   a. **Data transformation:** data was reshaped to long form and then collapsed to the period level, which resulted in data at the provider-period level (i.e. one row per

provider, per period).

b. Models without covariates: Models without covariates were first constructed for outcomes (1) - (3) to understand the unadjusted ordering patterns by provider. Additionally, a robustness check was done using two intervention washout periods. A one and two-month lag period were used to account for varying times for innovation diffusion.

c. Models with covariates: Building on the previous step, we next added covariates of interest (see section, Aim one: independent variables, above) to the model. Bivariate analysis was conducted to understand the empirical relationship between covariates and the outcome of interest. Covariates significant at the 0.10 level were included in the linear regression model. Backward elimination[127] was used to construct the final model, with covariates iteratively removed if the p-value was above 0.05. The final model contained only covariates with p-values less than 0.05.

Analytic Strategy – Aim 1.5 (Exploratory Analysis). This exploratory analysis focused on understanding ordering patterns by provider type. We conducted a descriptive statistical analysis as well as analysis of trends over time to identify differences in PLC ordering patterns (outcome 1) and PLC double lumen ordering (outcome 3) by attending physician, house staff (intern and resident), and nurse practitioner.

Aim one: sample size estimation. As this is the first study to evaluate the impact of a vascular catheter selection (PLC/MLC) CDSS on provider ordering behavior, there are no other studies to use as benchmarks for conducting a power analysis. For this study, estimates of the impact of this CDSS on provider and patient outcomes were based on studies that assess the impact of *clinical guideline-based CDSSs* on provider behavior. These types of studies are a useful proxy for effect since these types of interventions involved changes to professional culture and practice, which is often challenging to modify.[4] One study found that a CDSS intervention to

remove urinary catheters resulted in a 10-22% increase in orders for removal.[128] Review of the literature shows a similar trend for these types of studies.[4] Therefore, for **aim one**, we used a conservative estimate of the impact of the CDSS on provider ordering behavior: 10% reduction in the proportion of orders.

A recent preliminary analysis of data from one hospital within the University of Pennsylvania Health System found that PLCs comprised 84.9% of all PLC and MLC orders. Given a conservative **reduction of 10%,** we expected the post-intervention PLC ordering rate to be 76.4%. Linear regression of the continuous dependent variable (proportion of PLC orders) on continuous, normally distributed independent variables with a **sample size of 672** orders (336 sampled before and after the intervention) achieved an 80.022% power at a 0.05 significance level (alpha) to detect a difference between the group proportions of 0.0850. Since annual ordering of PLC and MLC catheters at HUP exceeds the required sample size at the conservative estimate, it is anticipated that this study will have adequate power for aim one.

Aim Two: Approach and Study Design

Aim two: study aim. To identify organizational, individual, usability, and workflow factors that impact provider CDSS acceptance, which we defined for this study as the willingness of users to use the system for the task that it was designed to support[35], and to elicit information about the impact of this system on communication between providers and the nurse-led vascular access team.

Aim two: approach and study design. We conducted a cross-sectional qualitative study of general medicine providers (attending physicians, resident and intern physicians, nurse practitioners) and vascular access nurses. Their perceptions of the value and usability of the system as well as the impact of the CDSS on workflow and inter-professional communication were gathered through a series of semi-structured interviews. The organization of care teams as

well as provider type characteristics were also explored to understand the relationship of these factors to system acceptance.

Aim two: sample and source. The sample consisted of ordering providers and vascular access team nurses. Providers (physician and advanced practice nurses) were recruited from the General Internal Medicine service at the Hospital of the University of Pennsylvania. This service was selected due to the frequent use and familiarity with the CDSS. Providers were randomly selected from the list of staff on call during the month of February and March 2017.

Vascular access nurses were recruited using convenience sampling from the vascular access team at the Hospital of the University of Pennsylvania, which consists of 10 specialty nurses solely dedicated to vascular access evaluation and placement; the first four volunteers were used for participation in this study. Physician sampling focused primarily on interns and residents since they are the heaviest users of the system; however, attending physicians were also interviewed. Sampling from both groups was initially **purposive**, with snowball sampling used to recruit additional participants.[129] By including a diverse set of participants (attending physicians, residents, interns, advance practice nurses, vascular access nurses), this sampling approach created a heterogeneous and information rich source of data for analysis. No reimbursement was provided to any participant.

Aim two: data collection. The investigator EJF conducted all interviews using a semi-structured interview technique. Prior to beginning the interviews, pilot interviews were conducted with two participants who fit the inclusion criteria, a VAT nurse and provider, to allow the interviewer to practice interviewing techniques and refine questions. Pilot interviews were discarded and not used in the analysis. Interviews were conducted with participants on site in a private area to allow participants to speak openly about their experiences with using the CDSS. Prior to the start of each session, each participant underwent a verbal informed consent process. All interviews were recorded using a digital audio recorder and transcribed using a transcription

service (CastingWords). Prior to recording, participants were instructed not to reference personally identifiable information. A quality review was done by EJF in which the documents of the transcribed audio interviews were reviewed against the original audio. Corrections were made by EJF as necessary. Audio files were destroyed after transcription. All participants were anonymized using a pseudonym selected from the list of the most popular names as defined by Social Security. The primary investigator maintains a list of participants and associated pseudonyms on a secure server within the University of Pennsylvania School of Nursing electronic network.[129]

The interview guide (See Appendix E for details) consisted of 12 broad, open-ended questions that were used to structure interviews (eight question for all providers and four additional for the VAT nurses). During the interview, open-ended probes were used to elicit additional information from the participants, such as "What was that like for you?". The interview guide was updated once to adjust for new themes as they emerged.[130] We added a question to understand from the VAT perspective the quality and accuracy of data entered by providers (Question 18). All notes created by the investigator (EJF) were organized immediately after each interview to avoid loss of information. Interview transcripts and field notes constituted the primary data source for this study aim.

Aim two: analytic strategy. Following cleaning to remove all identifiable information, transcripts were imported into a qualitative analysis software (Nvivo for Mac 11.4.0) to facilitate coding and analysis. Interview memos on links and relationships between concepts were recorded directly into this software and linked to transcripts as appropriate. All transcripts were read and heavily annotated before the start of qualitative coding.

We used a **conventional qualitative content analysis**, which is a line by line analysis of the text, to analyze the transcripts.[131] To remain true to the participants' own perceptions and voice, we used a low-inference and direct interpretation of transcripts; codes were generated

directly from participant comments.[131] In vivo codes were created based on direct participant quotes; codes were then used to construct the initial codebook. The codebook was tested on four transcripts (26.7% of the sample) and iteratively refined to reflect the data. The first four transcripts were double coded with the primary investigator (EF) and a researcher (WE) from the Mixed Methods Research Lab of the Department of Family Medicine and Community Health at the University of Pennsylvania [132] using NVivo 11 to calculate inter-rater reliability; all codes with a kappa of less than 0.75 were reviewed and differences were resolved by consensus. All codes in the final codebook had a kappa above 0.81 (cumulative kappa: 0.95).

Codes were analyzed across all participants to identify commonalities and differences. Themes emerged through the iterative process of analyzing the intersections between various codes. The final stage of the analysis involved the identification of core themes.

Aim two: rigor and trustworthiness. Final themes were reviewed by a researcher at the Mixed Methods Lab (WE) for **credibility** and **dependability**[129]. Credibility and dependability was confirmed by concurrent coding of data by both researchers (WE, EF) and evaluation of interrater reliability using qualitative software. **Confirmability** was achieved by maintaining an audit trail during the interview and analysis process. Field notes and memos were used to show how the categories and themes developed and to emphasize the links between the various steps in the data analysis process. **Transferability** was achieved by creating thick descriptions of all aspects of the study (e.g. setting, context) to assist other researchers in applying the approach to other studies. [129]

Protection of Human Subjects (aims one and two)

For aim one, data for this secondary analysis of retrospective EHR data was kept confidential and secure. All information was stored in electronic, password- protected folders, and all folders were stored on a secure, password protected server maintained by the University of Pennsylvania. Additional security measures included the physical and cyber-security of servers.

During the data analysis preparation phase, analytic datasets were prepared. No directly identifiable protected health information (PHI) were collected in this study. Indirectly identifiable PHI (i.e. admission and discharge dates) were collected. All dates were converted to categorical variables (e.g. period 1, period 2, period 3 and study month number). Analytic datasets did not contain any PHI. The original dataset received from the Penn DAC, which contains admission and discharge dates, were stored in a separate folder (password protected, on a secure UPHS server) from the analytic datasets. Risks to breaches in confidentiality of data were highly unlikely given the extensive security plan in place as described above and below. No data was saved to any local (i.e. C:\) drives.

For aim two, potential risks to participants included social and loss of confidentiality risks. Social risk: Some participants may be reluctant to share experiences or opinions for fear that their comments may be shared with UPHS administration. Although this risk is low, we addressed this risk by assuring participants of total anonymity and through building trust and rapport early on in the interview process. Interviews were conducted in a setting of the participant's choice; a private location away from other staff members was available as necessary. Loss of confidentiality risk: All interviews were confidential and all references to participant comments were de-identified. Furthermore, all audio taped interviews were deleted once transcribed. Data were anonymized before being put into electronic format. Electronic text documents, participant lists and codes were stored on a secure, firewall protected server and directory within the Penn School of Nursing.

CHAPTER 4: RESULTS

Aim One Results

Aim one: descriptive analysis - patient level data. During the study period (November 1, 2012 to October 31, 2015), there were 60,479 unique patients admitted to HUP (see tables 1A.1 & 1B.1). Of these patients, 7,391 had a catheter order placed by a provider (12.22%) via the CDSS. The findings from the descriptive statistical analysis revealed several key differences between the overall population and the population of patients for whom an order was placed (referred to from hereon as the "orders population"). The full tables can be found in Appendices F

Table 1A.1: Demographic and care organization information for admitted patients

	Overall	Period 1	Period 2	Period 3
Admitted patients (%)	60,479	21,274 (35.18)	17,691 (29.25)	21,418 (35.41)
Age: >=65	16819 (27.82)	4078 (19.18)	5737 (32.45)	6986 (32.64)
Sex, female	35364 (58.47)	12506 (58.79)	10295 (58.19)	12514 (58.43)
Race				
White	31703 (52.42)	10633 (49.98)	9452 (53.43)	11570 (54.02)
Black	22348 (36.95)	8578 (40.32)	6280 (35.50)	7450 (34.78)
Asian	1665 (2.75)	593 (2.79)	467 (2.64)	603 (2.82)
Unknown	4763 (7.88)	1470 (6.91)	1492 (8.44)	1795 (8.38)
Service Specialty Groups: *top 5, (%)*				
Surgery	33,612 (55.56)	12,232 (57.50)	9,863 (55.75)	11,463 (53.48)
General Medicine	14,136 (23.37)	5,072 (23.84)	4,098 (23.16)	4,942 (23.06)
Cardiovascular	4,419 (7.30)	1,555 (7.31)	1,338 (7.56)	1,521 (7.10)
Oncology	3,372 (5.57)	1,192 (5.60)	992 (5.61)	1,182 (5.51)
Cardiac Surgery	3,205 (5.30)	854 (4.01)	982 (5.55)	1,364 (6.36)

Table 1B.1: Demographic and care organization information for admitted patients with a catheter order

	Overall	Period 1	Period 2	Period 3
Admitted patients with orders (%)	7391 (12.22% of overall patient admissions)	2901 (39.25)	2175 (29.43)	2291 (30.99)
Age: >=65	2656 (35.94)	750 (25.85)	915 (42.07)	985 (42.99)
Sex, female	3445 (46.61)	1345 (46.36)	1021 (46.94)	1069 (46.66)
Race				
White	4616 (62.45)	1715 (59.12)	1406 (64.64)	1480 (64.60)
Black	1954 (26.44)	914 (31.51)	504 (23.17)	528 (23.05)
Asian	141 (1.91)	56 (1.93)	41 (1.89)	44 (1.92)
Other	677 (9.16)	216 (7.44)	224 (10.30)	239 (10.43)
Service Specialty Groups: *top 5*				
Surgery	2616 (35.39)	1030 (35.50)	832 (38.25)	744 (32.47)
General Medicine	2009 (27.18)	867 (29.89)	557 (25.61)	578 (25.23)
Oncology	1176 (15.91)	485 (16.72)	336 (15.45)	351 (15.32)
Cardiac Surgery	936 (12.66)	265 (9.13)	274 (12.60)	396 (17.29)
Cardiovascular	591 (8.0)	244 (8.41)	163 (7.49)	182 (7.94)

and G.

The two populations differed by age, patient acuity, medication use, and discharge disposition. The following section highlights the key differences and trends that impacted our analytical strategy. There are two tables that summarize data at the patient level: table 1A, contains data on the overall population, table 1B, is a subset of patients from 1A and contains data on patients who had at least one catheter order.

We noted trends and differences between the populations for several variables related to **patient demographics and organization of care** (Table 1A.1 & 1B.1). The percentage of older adults, defined as those aged **65 and older**, increased over time in the overall and orders population. For both groups, there was a large increase in period two (a 67% and 63% increase over the previous period, respectively). In the orders patient population, we noted that older adults constituted a higher percentage of the population, compared to the overall population. Approximately 36% of the order population were older adults, compared to 28% in the general population. Within the orders patient population, we noted an increase in the patients cared for by the cardiac surgical **specialty** across time periods.

Patient acuity. Patient acuity was assessed using several variables, namely APR-DRG weight, which are measures for classifying patients according to severity of illness and risk for mortality, number of discharge diagnosis per patient, creatinine clearance, length of stay (LOS), and ICU care.[121] A summary of the data for both patient populations can be found in tables 1A.2 and 1B.2. Overall, patients in the orders population had a higher acuity compared to the general population.

Table 1A.2: Acuity information for all admitted patients

Patient Acuity				
	Overall	**Period 1**	**Period 2**	**Period 3**
APR-DRG Weight				
Mean (SD)	1.73 (2.28)	1.64 (2.22)	1.75 (2.28)	1.80 (2.33)
Median (IQR)	1.01 (0.59, 1.86)	0.96 (0.57, 1.69)	1.02 (0.60, 1.96)	1.04 (0.59, 1.97)
DX per patient				
Mean (SD)	16.08 (11.09)	14.03 (9.74)	16.32 (10.88)	17.50 (11.96)
Median (IQR)	13 (8, 21)	11 (7, 18)	14 (8, 22)	14 (9, 23)
Creatinine Clearance: n (%) less than 30 *(indication of end stage renal disease)*				
Mean	3,397 (5.62)	1091 (5.13)	1101 (6.22)	1198 (5.59)
Median	3261 (5.39)	1040 (4.89)	1057 (5.97)	1158 (5.41)
Length of Stay				
Mean (SD)	5.95 (9.11)	5.54 (9.29)	6.08 (8.34)	6.24 (9.49)
Median (IQR)	3 (2, 6)	3 (2, 6)	3 (2, 7)	3 (2, 7)
ICU care (%)	4,652 (7.69)	1,526 (7.17)	1,402 (7.92)	1,716 (8.01)

The orders patient population had a longer median LOS and IQR compared to the overall population (10 (IQR: 18.69) vs 3 (IQR: 2, 6)). Median LOS in the orders patient population generally increased across the time periods; however, this increase was not reflected in the overall population. For patients in the orders patient population, median **APR-DRG weights** increased across the time periods, going from 1.91 (IQR: 1.01, 4.04) to 2.75 (IQR: (1.24, 5.81) in period three. This rate of increase was not observed in the overall population, going from 0.96 (IQR:

Table 1B.2: Acuity information for admitted patients with a catheter order

Patient Acuity				
	Overall	**Period 1**	**Period 2**	**Period 3**
APR-DRG Weight				
Mean	3.74	3.41	3.72	4.19
Median	2.21	1.91	2.24	2.75
DX per patient				
Mean (SD)	24.57 (13.73)	21.56 (12.29)	24.35 (13.01)	27.56 (14.94)
Median (IQR)	22 (15, 32)	19 (12, 28)	23 (15, 31)	24 (17, 35)
Creatinine Clearance: n (%) less than 30 *(indication of end stage renal disease)*				
Mean	435 (5.89)	168 (5.79)	145 (6.67)	121 (5.28)
Median	406 (5.49)	153 (5.27)	136 (6.25)	116 (5.07)
Length of Stay				
Mean (SD)	15.67 (18.69)	13.95 (20.07)	16.04 (16.16)	17.50 (18.96)
Median	10	8	11	12
ICU care (%)	448 (10.77)	312 (10.74)	215 (9.89)	400 (11.57)

0.57, 1.69) to 1.04 (IQR: 0.59, 1.57). The percentage of patients who received **ICU care** was higher in the orders patient population (10.77% vs. 7.69%). We noted a decrease in period two and then a rebound in period three, which was not reflected in the overall population.

Medications. Compared to the overall population, we noted that the orders patient population had higher percentage of intravenous (IV) medication administration for key medications. Within the orders patient population, we noted increasing trends across time periods for several variables (Tables1A.3 & 1B.3). The mean numbers of distinct intravenous medications administered and medication administration events, which is the total number of times medications were administered via IV to a patient, increased across time periods, moving from a mean of 9.97 to 11.31 for the number of medications and from a mean of 32.10 to 34.95 for medication administration events. Percentage of patients receiving vancomycin, other antibiotics, milrinone, and other IV medications increased across the time periods as well. The percentage of patients who received chemotherapy remained stable.

Table 1A.3: Intravenous medication information for all admitted patients

Intravenous Medications				
	Overall	**Period 1**	**Period 2**	**Period 3**
Medications per encounter, n				
Mean (SD)	5.11 (5.23)	5.01 (5.17)	5.22 (5.25)	5.11 (5.25)
Median (IQR)	3 (2, 6)	3 (2, 6)	4 (2, 6)	3 (2, 6)
Medication administrations per encounter, n				
Mean (SD)	12.92 (19.96)	13.08 (20.38)	13.15 (19.88)	12.54 (19.53)
Median (IQR)	6 (3, 14)	6 (3, 15)	7 (3, 15)	6 (3, 14)
Medications administered by category, n (%)				
Category medications administered, n (%)				
Vancomycin	10569 (20.05)	3418 (18.33)	3211 (20.58)	3920 (21.34)
Other antibiotics	30886 (58.61)	10774 (57.77)	9215 (59.07)	10843 (59.04)
Milrinone	957 (1.82)	283 (1.52)	317 (2.03)	355 (1.93)
Chemotherapy	2016 (3.83)	740 (3.97)	568 (3.64)	705 (3.84)
Other IV Meds	38465 (72.99)	13641 (73.14)	11540 (73.97)	13213 (71.95)
Patient Controlled Analgesia	12760 (24.21)	4768 (25.57)	3802 (24.37)	4171 (22.71)

Table 1B.3: Intravenous medication information for patients with a catheter order

Intravenous Medications				
	Overall	Period 1	Period 2	Period 3
Medications per encounter, n				
Mean (SD)	10.56 (8.39)	9.87 (8.31)	10.66 (8.34)	11.31 (8.42)
Median (IQR)	8 (4, 15)	7 (4, 13)	9 (4, 14)	9 (5, 16)
Medication administrations per encounter, n				
Mean (SD)	33.42 (22)	32.10(20)	33.37 (23)	34.95 (24)
Median (IQR)	22 (9, 45)	20 (8, 43)	23 (10, 46)	24 (11, 46)
Medications administered by category, n (%)				
Vancomycin	3623 (50.67)	1266 (45.49)	1079 (51.02)	1267 (56.82)
Other antibiotics	5473 (76.55)	2039 (73.27)	1644 (77.73)	1772 (79.46)
Milrinone	483 (6.76)	159 (5.71)	144 (6.81)	179 (8.03)
Chemotherapy	982 (13.73)	393 (14.12)	272 (12.86)	316 (14.17)
Other IV Meds	6273 (87.73)	2397 (86.13)	1860 (87.94)	1995 (89.46)
Patient Controlled Analgesia	1963 (27.45)	780 (28.03)	585 (27.66)	590 (26.46)

The results from the descriptive statistical analysis showed several differences between the two populations in factors key for this analysis, namely percentage of older adults, service, patient acuity, and medication use. Trends were also noted within the orders population, which led to a sub-analysis of orders data to understand how these sub-groups might impact our outcomes of interest.

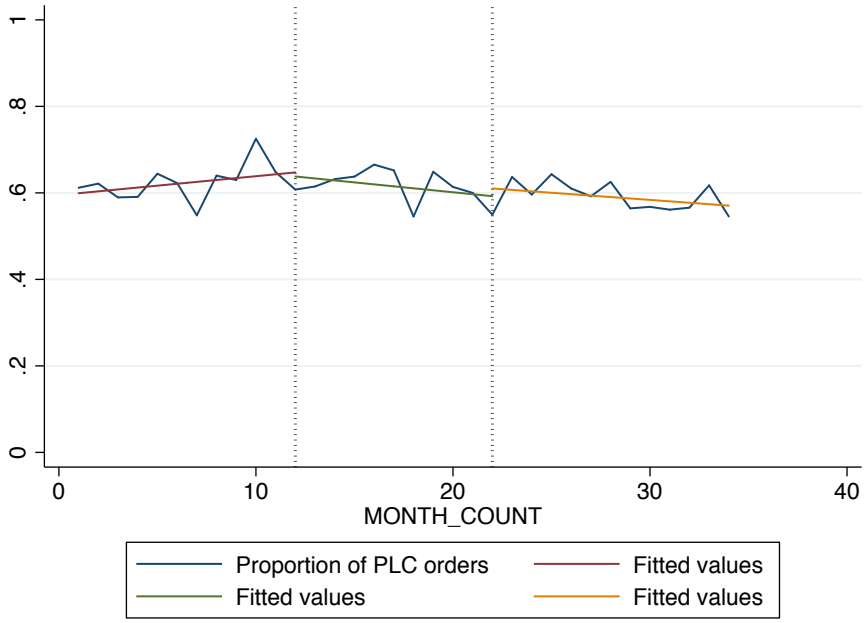
We performed a sub-analysis on orders data for key categorical variables, namely age, and provider service, using logit regression models. The intent of these tests was to understand how these sub-groups impacted our main outcome of interest – proportion of PLC orders (1). Our findings showed that the trends remained at the 0.05 p-value level even when the data from these groups were excluded, implying that these groups were not driving the observed trends.

Aim one: analysis of ordering over time. The following section contains results for the part two of the analytic strategy – analysis of outcomes over time (see Appendix H for details).

Proportion of PLC orders (A1.1). In this study, we hypothesized that the CDSS would result in a decrease in the proportion of PLC orders due to the decision support intervention being embedded within existing workflow. Our hypothesis was *partially* supported: results showed a statistically significant decrease in the proportion of PLC orders created between the periods one

and three (p-value: 0.04). The difference between periods one and two was not statistically significant. In the pre-intervention period, the proportion of PLC orders increased across time (slope of the line: 0.006). After the introduction of the CDSS, the slope of the line decreased in both periods two (slope: -0.002) and three (slope: -0.003). There is a significant difference between the slope of the line in period one and period three (p-value: 0.04).

Figure A1.1: Proportion of PLC orders over time (months), with fitted line



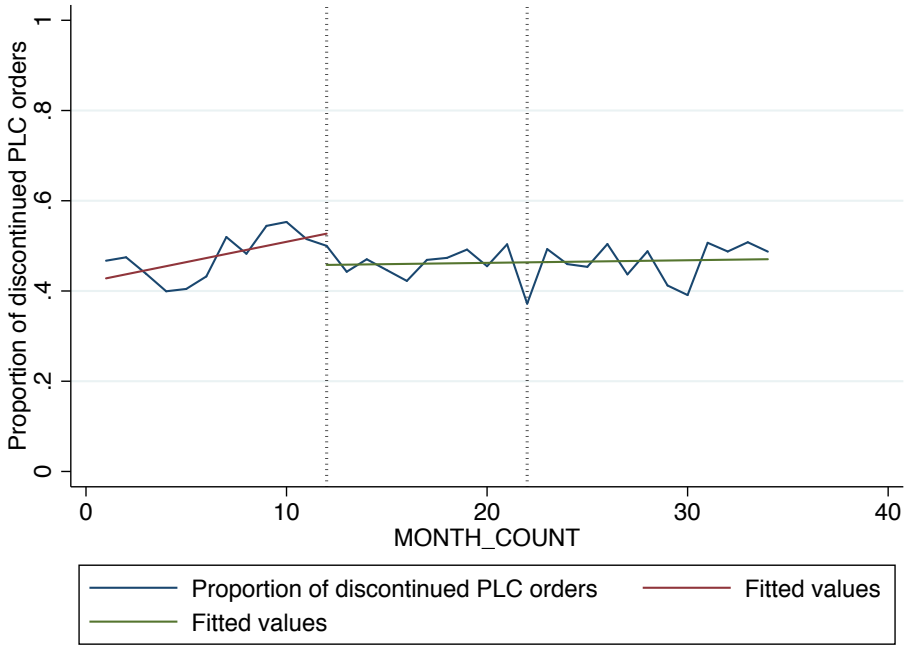
* Vertical lines demark time between study periods 1&2 and 2&3

There are several peaks and troughs evident in the plot and several of these coincide with the on-boarding of new house staff (interns and residents), which is also known as the "July Effect" (Figure A1.1). We noted an increase in the proportion of PLC orders in study-month nine, which occurred in July 2013 (0.63 for month nine and 0.73 for month 10). In the following July period (2014, study-month 21), we noted a decrease in the proportion of PLC orders (0.60 for month 21 and 0.55 for month 22). In the third July (2015, study-month 33), we noted an initial bump in the proportion of PLC orders followed by a drop off (0.62 for month 33 and 0.55 for

month 34). When the model was adjusted for the July effect, there was no change in statistical significance between periods.

Proportion of discontinued PLC orders (A1.2). In this study, we hypothesized that by providing decision support to the provider at the time of order creation, the CDSS would result in an increase in the proportion of PLC orders that were aligned with evidence-based recommendations. In the data, we expected to see a decrease in the proportion of discontinued orders (i.e. orders rejected by VAT nurses). Our hypothesis was not supported: there is no statistically significant difference in the proportion of discontinued PICC orders between the study periods. Estimated mean proportion of discontinued PLC orders in period one was 0.48, whereas after the intervention the proportion decreased to 0.47 and 0.46 for periods two and three. However, there is a notable difference between the trend pre and post-intervention of the CDSS. The slope in the pre-intervention period was 0.01, while the slope in the post periods were 0.002 and 0.004 respectively. When periods two and three are evaluated together (slope: 0.005, Figure A1.2), the difference between the pre-intervention and post-intervention slopes is statistically significant (p-value: 0.02).

Figure A1.2: Proportion of discontinued PLC orders over time (months)



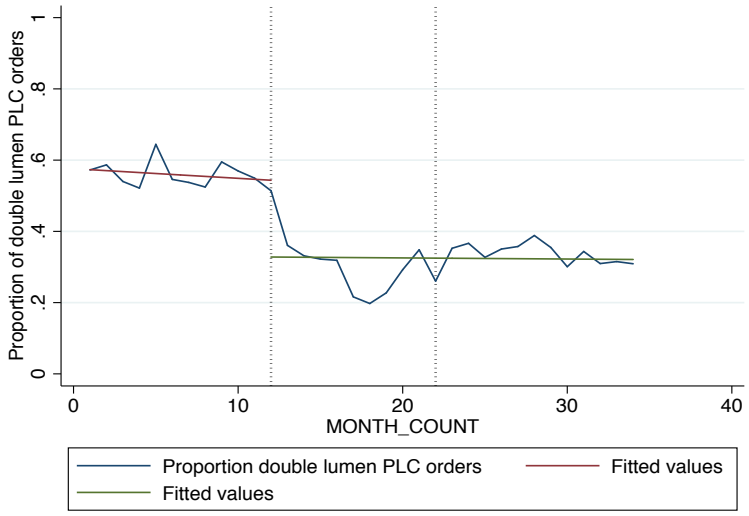
* Vertical lines demark time between study periods 1&2 and 2&3

Proportion of double lumen PLC orders (A1.3). We defined the proportion of double lumen orders as double lumen PLC orders divided by total PLC orders per month. We hypothesized that the CDSS would results in a decrease in the proportion of double lumen orders due to the provision of decision support at the provider level at the time of order creation and single lumen default for most treatment requirement scenarios. Our hypothesis was supported: results showed a statistically and clinically significant decrease in the proportion of double lumen orders created after the intervention was introduced. Estimated mean proportion of double lumen orders in the pre-intervention period was 0.56, whereas the mean in the post-intervention periods was 0.31 and 0.33, respectively (p-value: <0.001).

In examining the data over time, while the trend during the pre-intervention period (Figure A1.3) already showed a slight decreasing trend in the pre-intervention period (slope: -

0.001), this decrease occurred immediately before the intervention (study-month 11). The post-intervention trend, across periods two and three, is mostly flat (slope: -0.0003).

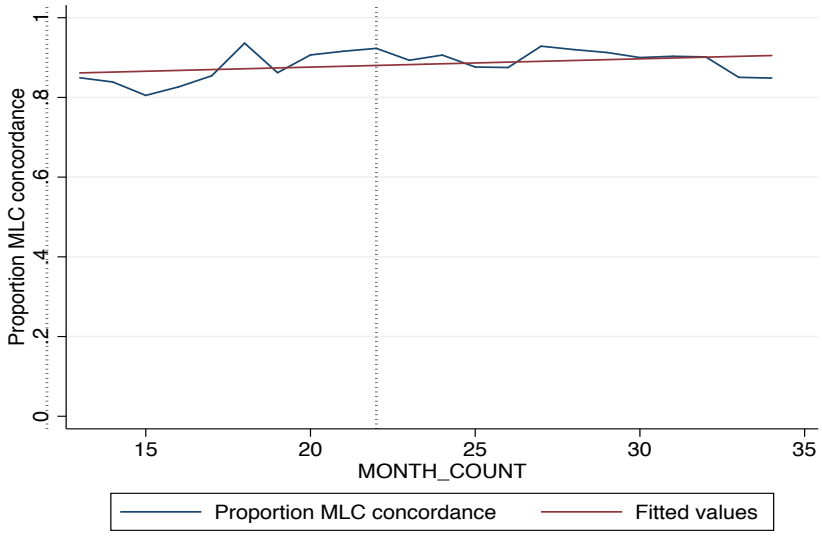
Figure A1.3: Proportion of double lumen PLC orders over time (months)



* Vertical lines demark time between study periods 1&2 and 2&3

MLC recommendation concordance (A1.4). We defined MLC recommendation concordance as the number of MLC orders entered by a provider, given that the CDSS recommended a MLC order, divided by the number of CDSS MLC order recommendations (see Appendix D for variable definition). We hypothesized that the order concordance would increase over time. Our hypothesis was not supported: results show a slight, non-statistically significant increase in MLC concordance over time (p-value 0.09). Mean MLC concordance in period two was 0.87 (SD: 0.05) vs. 0.89 (SD:0.04) in period three.

Figure A1.4: MLC Concordance over time (months) with fitted values



* Vertical lines demark time between study periods 2 and 3

Aim one: variance component models. To account for similar ordering patterns within individual providers, the next level of analysis included clustering by individual providers. Data was transformed from the order level to provider level by calculating the proportions for each outcome by provider ID and period. Unadjusted and adjusted models were created for outcomes (1) – (3). To adjust for covariates (see section, aim one: independent variables in chapter four) in the model, bivariate analysis was conducted to understand the empirical relationship between covariates and the outcome of interest. Covariates significant at the 0.05 level were included in the regression model. Backward elimination[127] was used to construct the final model, with covariates iteratively removed if the p-value was above 0.05. The final model contained only covariates with p-values less than 0.05. See Appendix I for a list of covariates and results from the bivariate analysis.

Proportion of PLC orders, clustering by provider (A1.1). We hypothesized that the CDSS would result in a decrease in the proportion of PLC orders due to the decision support intervention being embedded within existing workflow. When clustering by provider was taken

into account, results for the unadjusted and adjusted models show that our hypothesis was not supported, which differed slightly from the previous unadjusted analysis of *orders* data (results for the unadjusted analysis of orders data, which did not account for clustering, found a statistically significant difference between periods one and three). The estimate for the mean number of PLC orders entered per provider and period did not change between periods one and two and decreased between periods one and three for the unadjusted models. The difference between period one and three was not statistically significant. In the adjusted models, there was a slight increase in period two and then decrease in period three. All differences were not significant (Tables A1.1A & A1.1B).

Table A1.1A: Estimates for the proportion of PLC orders per provider and period

Period	All data	Adjusted model (All)	Limited dataset	Adjusted model (Limited)
	Estimate			
1	0.62	0.62	0.63	0.62
2	0.62	0.63	0.64	0.64
3	0.60	0.60	0.58	0.58

Table A1.1B: p-values for comparison of estimates between periods

Period	All data	Adjusted model (All)	Limited dataset	Adjusted model (Limited)
	p-values			
1 & 2	0.89	0.57	0.64	0.19
1 & 3	0.24	0.34	0.04	0.12
2 & 3	0.31	0.13	0.01	0.007

We created a subset of the data and included only providers who provided data during the pre and post interventions periods (column three of tables) and created both unadjusted and adjusted models using this dataset. Results differ from the previous results: in the adjusted model,

there was a statistically significant decrease in the mean proportion of PLC orders between providers between periods one and three. However, these differences disappeared when the model was adjusted.

We conducted robustness checks to account for possible delays in use of the CDSS or in learning about the CDSS functionality. When the intervention period cut-off was moved one month (from month 12 to month 13), results remain unchanged from the previous analysis of the limited dataset (column three).

Proportion of discontinued PLC orders, clustering by provider, unadjusted models (A1.2). We hypothesized that by providing decision support to the provider at the time of order creation, the CDSS would result in an increase in the proportion of PLC orders that were aligned with evidence-based recommendations. In the data, we expected to see a decrease in the mean number of discontinued orders by provider (i.e. orders rejected by VAT nurses). When clustering by provider was taken into account, our hypothesis was not supported, which was consistent with the previous unadjusted analysis of orders data. The estimate for the mean number of discontinued PLC orders entered per provider and period decreased between periods one and two and increased between periods one and three (table A1.2A); however, the differences was not statistically significant (see table A1.2B for p-values for comparison between periods).

Table A1.2A: Estimates for the proportion of discontinued PLC orders per provider and period

Period	All data	Limited dataset
	Estimate	
1	0.46	0.47
2	0.45	0.45
3	0.47	0.48

Table A1.2B: p-values for the proportion of discontinued PLC orders per provider and period

Period	All data	Limited dataset
	p-values	
1 & 2	0.63	0.46
1 & 3	0.82	0.73
2 & 3	0.49	0.32

We created a subset of the data and included only providers who provided data during the pre and post interventions periods (column two of tables A1.2A and A1.2B). Results remain unchanged: there was no statistically significant difference in the proportion of discontinued PLC orders entered by provider per period. We did not adjust our models for this outcome given the multiple results indicating that differences were not statistically significant.

Proportion of double lumen PLC orders, clustering by provider (A1.3). We hypothesized that the CDSS would result in a decrease in the proportion of double lumen orders due to the provision of decision support at the provider level at the time of order creation and single lumen default for most treatment requirement scenarios. When clustering by provider was taken into account, results for the unadjusted and adjusted models show that our hypothesis was supported, which was consistent with earlier unadjusted analysis at the order level. Results for clustering standard errors by individual providers are consistent with earlier findings. Findings indicate that estimates of the mean proportion of double lumen orders created by provider decreased after the

Table A1.3A: Estimates for the proportion of double lumen PLC orders per provider and period

Period	All data	Adjusted model (All)	Limited dataset	Adjusted model (Limited)
	Estimate			
1	0.85	0.84	0.84	0.83
2	0.37	0.38	0.37	0.38
3	0.50	0.51	0.46	0.46

Table A1.1A: p-values for the proportion of double lumen PLC orders per provider and period

Period	All data	Adjusted model (All)	Limited dataset	Adjusted model (Limited)
	p-values			
1 & 2	<.0001	<.0001	<.0001	<.0001
1 & 3	<.0001	<.0001	<.0001	<.0001
2 & 3	<.0001	<.0001	0.002	0.012

intervention (Tables A1.3A & A1.3B). The differences between periods one and two and periods one and three are statistically significant. There is also a statistically significant increase in the mean proportion of orders created per provider between periods two and three. Covariates for the adjusted model and results from the bivariate analysis can be found in Appendix I.

We created a subset of the data and included only providers who provided data during the pre and post interventions periods (column two of tables). Results were consistent with the previous analysis and remained highly statistically significant.

We conducted robustness checks for outcomes (1) - (3) by conducting the above analysis with clustering at the unit level. Results for this analysis were consistent with the analysis presented above.

Aim one: exploratory analysis - examining differences in ordering patterns by provider type and service (A1.5). We conducted a statistical analysis to identify differences in PLC ordering patterns (A1.1) and PLC double lumen ordering (A1. 3) by period and (1) provider type (i.e. attending, house staff (intern and resident), and nurse practitioner) and (2) service. To account for similar ordering patterns within individual providers, we clustered the data by individual provider. In addition, we analyzed differences in the full dataset as well as in the limited orders dataset (e.g. providers with data in both the pre and post study period). Differences were noted in the analysis with provider type.

Provider type. We hypothesized that there would be differences in ordering in provider types; our hypothesis was partially supported. Overall, there were no statistically significant differences in ordering within provider type within the full dataset – for both A1.1 (proportion of PLC orders) and A1.3 (proportion of double lumen orders). When patterns were examined in the limited dataset, we noted differences only in the proportion of PLC orders (A1.1).

Table A1.5-A shows the estimated mean proportion of PLC orders by provider type, per period. In examining PLC ordering patterns, by provider type, between periods in the limited dataset, we found a decreasing trend in the proportion of PLC orders for house staff (interns and residents), with a statistically significant decrease between periods one and three and periods two and three (Table A1.5-B). For nurse practitioners, there was an increasing trend in the proportion of PLC orders between periods, with a statistically significant increase between periods one and three. For attending physicians, there was an increase in the proportion of PLC orders between periods one and two (non-significant) and a statistically significant decrease between periods two and three.

Table A1.5-A: Estimates for proportion of PLC orders by period and provider type (limited dataset)

Limited Dataset			
Period	**Attending**	**House**	**NP**
	Estimates		
1	0.53	0.68	0.54
2	0.61	0.65	0.60
3	0.50	0.57	0.65

Table A1.5-B: p-values for the differences, by provider type and period, in PLC proportion (limited dataset)

Limited Dataset			
Period	**Attending**	**House**	**NP**
	p-values		
1 & 2	0.08	0.38	0.25
1 & 3	0.64	0.0003	0.047
2 & 3	0.07	0.01	0.39

Basic descriptive statistics related to patient acuity by provider type show that median APR-DRG, which is an indicator for severity of illness and resource consumption, for house staff stayed relatively stable across time periods (Tables A1.5-C and A1.5-D below); however, median values increase for nurse practitioners (4.04 to 5.29 in period 3). Median LOS followed a similar pattern.

Service. We hypothesized that there would be differences in ordering by service; our hypothesis was not supported. We compared models with and without interactions between service (general surgery, cardiac surgery, and general medicine) and period (using the full and limited datasets). Overall, there were no statistically significant differences between the models for both A1.1 (proportion of PLC orders) and A1.3 (proportion of double lumen orders).

Table A1.5-C: Median APR-DRG weight, by provider type & period (IQR)

Period	Attending Physician	House Staff	Nurse Practitioner
1	2.43 (1.22, 5.30)	2.55 (1.31, 5.30)	4.04 (1.92, 7.88)
2	2.20 (1.15, 5.81)	2.54 (1.22, 5.57)	4.66 (2.54, 7.48)
3	2.81 (1.23, 6.99)	2.81 (1.24, 5.81)	5.29 (2.54, 8.82)

Table A1.5-D: Median patient length of stay, by provider type & period (IQR)

Period	Attending Physician	House Staff	Nurse Practitioner
1	13 (8, 25)	14 (7, 28)	15 (8, 29)
2	13 (7, 25)	15 (8, 27)	16 (10, 27)
3	21 (9, 39)	15 (8, 29)	17 (10, 29)

Aim Two Results

We conducted 15 semi-structured interviews of providers within the general internal medicine service line at the Hospital of the University of Pennsylvania(HUP) from February to March 2017. To determine whether provider responses varied by either the type and level, we purposively sampled participants from the following five groups: (1) nurse practitioner (NP), (2) attending physician (MD), (3) resident MD, (4) intern MD, and (5) vascular access team (VAT) nurse. Table A2 below contains a summary of participant distribution by group. As a whole group analysis, saturation was reached with these 15 participants.

Table A2: Description of Study Participants

Type	Number of Participants, N=15 (%)	Service Line/Function
Provider (NP, MD)	11 (73.3)	General Medicine (Martin 1-6)
RN	4 (26.6)	Vascular Access Insertion Team
Provider Type / Level		
NP	2 (13.3)	General Medicine, non-teaching (Martin 6)
Attending, MD	2 (13.3)	General Medicine, teaching (Martin 1-5)
Resident, MD	4 (26.6)	General Medicine, teaching (Martin 1-5)
Intern, MD	3 (20.0)	General Medicine, teaching (Martin 1-5)

Three themes emerged from the data: 1) education and decision support for evidence-

based practice; 2) inter-professional communication; and 3) process efficiency. Participant narrative examples are used to enhance understanding of the context in which these qualitative findings exist. Relevant model constructs have been mapped to each of the resulting themes (see theoretical model in chapter three for more information on constructs for the Socio-Technical Model for Studying Health Information Technology in Complex Adaptive Healthcare Systems (STM) by Sittig and Singh[87]).

Theme 1: the CDSS facilitates education and decision support regarding evidence-based practice (*Model constructs: People, Clinical Content, Organization, and Human Computer Interface)*. Most participants discussed how the CDSS provided education on evidence-based practice for PICC line catheter (PLC) and midline catheter (MLC) indications and risks. Ordering providers talked about how these educational opportunities occurred at the point of care, which provided multiple opportunities for learning reinforcement. While this was a constant theme across all ordering provider types, the degree to which the CDSS influenced decision making varied by provider clinical experience level.

Providers frequently shared that the information presented via the CDSS was their first exposure to evidence-based recommendations for PLC and MLC risks and indications

> ...certainly, at no point would I have been taught what the benefit was of a Midline over a PICC, or infection differences or what the algorithm could look like. I think, in this particular case, coming from an unformed opinion, it [the CDSS] formed the opinion. – *Mia, Physician, Post Graduate Year 3*

Additionally, half of the resident physician participants explained, while certain patient care decisions can be the topic of considerable discussion for a care team (e.g. blood transfusion or medications decisions), PLC and especially MLC decisions are deemed to be more peripheral and are not explicitly the focus of discussion and debate with care teams. Thus, the lack of prior exposure coupled with the peripheral focus in the clinical setting appeared to increase the value of the CDSS, especially for the more novice provider.

While the more novice providers shared how the CDSS provided education, more experienced providers stated that repeated use of the tool was instrumental in helping them to commit recommendations to memory.

> I've learned a lot from this order set. I know now what warrants a PLC and what warrants a MLC. For me, I feel like I can order intelligently without that [the CDSS]. For people that haven't used an order set, like new interns and things, I feel like we'll go back to whatever problems we had with the old order set [e.g. ordering off evidence]. – *Liam, physician, Post Graduate Year 4*

> Then it taught me what to do, but if I hadn't had this, I don't know that I would know the algorithm to do a MLC versus a PLC. It's just from constant repetition, that you learn that way. – *Mia, physician, Post Graduate Year 3*

Theme 2: impact on inter-professional communication (*Model constructs: People, Workflow and Communication, and Human Computer Interface)*. Most participants stated that the CDSS positively impacted communication between the ordering providers and VAT nurses by standardizing and streamlining the transfer of information between teams. However, many also described how the tool presented communication challenges for ordering scenarios that fell outside of the scope of the CDSS algorithm.

Although many providers did not populate all fields listed in the CDSS, information for the most essential decision factors, such as medication type/category, duration, and whether a double lumen or single lumen were necessary, were consistently populated by the ordering provider. Both groups stated that standardizing data collection helped to streamline communication. Communication improvement had different meaning for the two groups. From the provider perspective, communication was improved by allowing for asynchronous communication of critical data to the VAT nursing team.

> It just streamlines things, because we're able to list what meds we're getting and why we're asking, instead of just a blank order, "They [patient] need[s] a PICC," and then they [VAT nurse] would have to call, "Why do they need a PICC? What meds? This [the order generated from the CDSS] already says either antibiotics for this long or multiple access points for this long*."— Noah, Physician, Post Graduate Year 1*

From the VAT nurse perspective, communication improved because the CDSS primed the conversation between the provider and nurse: when a VAT nurse called the provider for follow-up, the provider knew exactly what the conversation would entail.

> I think, a lot of times, they're OK with us discussing the plan and reviewing what's the best access for their patient... they're receptive because they did answer these questions. They know that these are questions that we have to consider. We're not just firing questions at them because we're trying to be difficult. These are things that we have to consider when placing a line. — *Emily, VAT Nurse*

One of the two attending physicians interviewed, who had experience with ordering venous access devices before the CDSS was implemented, stated that in standardizing the collection of data elements and providing catheter type recommendations in advance of the follow-up conversations, the CDSS also helped to reduce miscommunication and tension between the two groups.

> I would say, I think, if you don't know why things are wrong, the communication can be very frustrating. It can always start off at a very different level than just being a very academic and a fruitful discussion. You have 23-year-olds to 45-year-olds doing the same thing and being overworked, and they get frustrated, and they'll be like, "Oh, this person's not listening to me, blah blah blah."... Versus now, it's like, oh, this is something that they're [VAT RNs] not putting up a stink about, it's something that's evidence-based, and they [interns, residents] sometimes work with it better. I think having this tool has definitely been helpful to make conversations more streamlined, more professional sometimes... – *Sophia, Attending Physician*

Although both groups stated that the CDSS improved communication overall, many providers and VAT nurses provided examples of how limitations in the CDSS rules engine and interface design presented communication challenges for common patient care scenarios. These types of challenges were discussed for two specific scenarios, patients requiring post-acute care other than home care, and patients requiring frequent blood draws, which resulted in multiple rounds of communication and delays in patient care.

A flag to communicate post-acute home care infusion requirements was implemented in version two of the CDSS; however, the design did not account for other common discharge disposition locations, such as skilled nursing facilities (SNFs). Some post-acute care facilities are more likely to only accept patients discharged with PLCs, even when the treatment and duration would normally indicate a MLC, and the CDSS design did not provide guidance for this situation.

> The problem is that it [CDSS] doesn't distinguish -- a lot of SNFs and Penn Home Care or different home-care services won't take Midlines. Because it has happened a few times where we put in a Midline thinking we were doing the right thing, and then the SNF wouldn't take them and they had to go back to the PICC line. — *Mia, Physician, Post Graduate Year 3*

Similar challenges were discussed for patients requiring frequent blood draws as the CDSS rules engine and interface did not account for this patient care scenario. In this situation, the CDSS limitation resulted in additional work on the provider side, as a new order would have to be created and the old order discontinued. However, some providers developed workarounds for this scenario.

> For difficult sticks or for frequent blood draws...I type in other IV medications [in the PICC/Midline order set], and then I explain. – *Olivia, Attending Physician*
> They'll [providers] most likely click off "other antibiotics," and then they can put in comments. Sometimes they'll comment, "Multiple repletions, blood transfusions, blood draws." They'll write in a comment that will print out for us. – *Abigail, VAT nurse*

Providers also described challenges in communicating order information for special case orders or in cases of recommendation overrides as the interface did not have a field for notes or comments. Participants described workarounds for these situations:

> I'll often change the parameters so that it recommends for me a PICC... I'll change something that I know would require a PICC. For instance, vanco's always going to require a PICC. You could push Vanco, and then, the PICC orders will come up...If you click other IV antibiotic, other IV meds, you get free text...That's how I'll communicate with the PICC team. – *Liam, Physician, Post Graduate Year 4*

Theme 3: the CDSS impact on process efficiency *(Model constructs: Workflow and*

*Communication, People, and Organization)***.** Most providers commented on how the CDSS improved work efficiency for routine orders, though different provider groups defined improvements to process efficiency in distinct ways. From the VAT perspective, the CDSS provided a summary of the essential elements required for performing vascular access evaluation, which resulted in time saved during their chart review.

> If it didn't print out what they think that they need the line for, then we would have to find it somewhere in their care plan, where they write the plan, or somewhere in their recommendations from nutrition or whatever if they need TPN. The plan does at least give us a quick picture of the patient to be like...Maybe it's for vancomycin. "Let's check their meds. Are they on vancomycin?" It just at least gives us a head start on why they're ordering the line...I definitely like the creat. [creatinine]. The creat, I mean, that's always accurate, and it's always nice to know if it's above three, below three. — *Charlotte, VAT Nurse*

From the ordering provider perspective, participants described entering venous access orders as just another task that needs to be completed and stated that the CDSS allowed them to efficiently and quickly eliminate these tasks from their list.

> It's hugely convenient. It's one last call that you need to make. — *Isabella, Physician, Post Graduate Year 1*

> It streamlines the process. If I wanted to have a procedure done on a patient, I call procedure service to do this, rather than having to answer a bunch of questions over the phone that are very routine, and this outlines all the questions they would want to know. It saves, I guess, time that way. — *Mia, Physician, Post Graduate Year 3*

CHAPTER 5: DISCUSSION

Aim One

This study sought to understand the impact of a CDSS designed to align provider PLC and MLC vascular catheter ordering behavior with evidence based recommendations. We conceptualized ordering behavior as (1) the proportion of PLC orders entered of all catheter orders (A1.1), (2) proportion of discontinued PLC orders of all PLC orders (A1.2), (3) proportion of double lumen orders (A1.3) of all PLC orders, and (4) order concordance, which was defined as percent agreement between CDSS recommended MLC orders and the order submitted by a provider(A1.4).

Results from our analysis of these outcomes was mixed. When clustering by provider was taken into account, we found that the CDSS did not have a statistically significant effect on the **proportion of PLC orders created by providers** or on the **proportion of PLC orders discontinued**; however, we found a large clinically and statistically significant effect of the CDSS on the **proportion of double lumen orders** submitted by providers. The results also showed that **MLC order concordance** did not change between the two intervention periods. These results were somewhat unexpected given the large body of literature that has shown CDSSs, especially those that prompt users with recommendations, to be effective in changing provider performance.[77,78]

Although the data appears to show only a modest clinical impact of the CDSS on the **proportion of PLC orders**, results from analysis of order concordance reveal a potential explanation for this apparent lack of effect. Our analysis of order **concordance f**or both MLC and PLC found high rates for CDSS recommendation and provider order agreement, starting immediately after the introduction of the CDSS and lasting throughout the entire study period. Additionally, when concordance rates were assessed over time, we found that the standard

deviation narrowed in period three. Taken together, the high adherence rates to CDSS PLC and MLC recommendations may indicate that there was limited opportunity for improvements in provider PLC ordering behavior. It is important to include the vascular access team, an organizational level change introduced in 2010, when interpreting these results. This team was responsible for reviewing each PLC and MLC order placed by providers and was likely a significant influence on provider PLC ordering behavior. The impact of vascular access teams is supported in the literature; research had shown that these teams are effective in helping to improve adherence to evidence based practices.[133] In this setting, VAT nurses would typically have a discussion with ordering providers for PLC or MLC orders that were not aligned with evidence-based recommendations, with orders then discontinued. Therefore, it is likely that provider PLC ordering during the study period may have already been aligned with evidence based practice, thus reducing the differential impact of this additional CDSS intervention.

When ordering patterns were examined **by provider type** (e.g. house staff, nurse practitioner), the CDSS appears to have had a differential impact, in particular with house staff (i.e. interns and residents) and nurse practitioners. For house staff, there was a modest (non-statistically significant) decrease in the proportion of PLC orders created between periods one and two and a statistically significant decrease between periods one and three and two and three. Given that the major system policy and procedure disruption was contained in the initial version of this CDSS (version two of the CDSS was implemented on August 26, 2014 and contained relatively few changes compared to the initial version), the statistically significant decease between periods one and three and two and three were unexpected. These results are based on analysis for a subset of providers that had data in both the pre and post-intervention periods. When we examined the full dataset, which included provider data even if they had only created orders in a single period, the differences between periods were no longer apparent. In light of the previous discussion regarding the impact of the VAT, it is possible that the effect observed in

period three was due to the VAT review process. We know from prior research findings (aim two of this study) that providers, both physicians and nurses, do not receive training on PLC/MLC indications and risks while in graduate school (medical school or advanced practice nurse master of science programs). Given that most house staff enter relatively few orders (75% of house staff entered less than 11 orders in period one and two, each), it is possible that the impact of the VAT review took until period three to be achieved for house staff. Another potential explanation for the limited impact lies in organization of care teams: interns receive much of the day-to-day training and instruction from senior level residents. While interns place many of the PLC and MLC orders, in many instances this occurs after consultation with senior level residents (who also received informal training on this topic from the VAT). A new group of interns arrived in study-month nine, which was right before the intervention of the CDSS (study-month 12). It is possible that senior residents advised new house staff on PLC and MLC ordering best practices.

With regards to nurse practitioners, we saw an increase in the proportion of PLC orders entered across the study periods, with the difference between periods one and three being statistically significant (mean proportion of PLC orders increased from 0.54 in period one to 0.64 in period three (p-value 0.045)). Similarly, we expected to see a difference between periods one and two given that the first CDSS version introduced contained the most significant changes. When comparing patient acuity (APR-DRG weight and LOS) between house staff and nurse practitioners, nurse practitioners appeared to care for a higher acuity patient population and this acuity increased over time, which could explain relative increase in the proportion of PLC ordered over time. Research regarding differential impact of CDSS by provider groups is limited; pre research has not found evidence for differences between provider types (trainee vs. attending physicians).[78] Additional research is needed to understand other factors that may have differentially impacted ordering behavior between these provider groups.

Regarding the dramatic impact of the CDSS on **double lumen PLC orders**, this raises the question as to why the VAT review process did not have a similar impact on double lumen orders. There are three potential explanations for this including, (1) nascent evidence base regarding double lumen PLCs and associated risks; (2) challenges in keeping abreast with drug-drug incompatibility, which is a major indication for the use of double lumen PLCs; (3) lack of organizational policy regarding double lumen PLCs before the CDSS implementation. Regarding the first point, a review of the 2011 Nurse Infusion Society Standards for vascular access device selection showed a lack of guidance for double lumen indication.[134] For point number two, the challenges of recalling drug information, including interactions and compatibility, are well documented in the literature. The success of computerized provider order entry EHR modules for medication ordering has been attributed in part to automated use of drug formularies for drug-drug interactions and incompatibilities.[135] Regarding point three, in 2012, UPHS created a set of PLC and MLC ordering recommendations based on expert opinion and a systematic review of the literature; these recommendations included guidance for double lumen PLC use. In turn, these recommendations formed the basis for the CDSS rules engine; the CDSS was then used as the mechanism in which to implement the organizational policy and procedure change.

The design of the CDSS interface likely also played a role in reducing the proportion of **double lumen PLC** orders. In this case, functionality for ordering a double lumen was implemented as a check-box in the lower left corner of the screen (on the opposite side of the screen as the "okay" button). The check-box defaulted to null in most cases (exception being for certain medications such as TPN and home care infusion requirements such as milrinone). Several recent studies have assessed the use of defaults in medication ordering and have found this design approach to be effective in changing ordering patterns. For example, Bourdeaux et al. created order set templates with default medication bundles. Providers could choose to opt out of medications, but they had to select medications manually, which was more time consuming.

Prescribing rates for these medication bundles increased significantly compared to before the intervention.[96] Similar strategies have been applied in other studies with similar outcomes.[32,34]

With regards to null findings related to **discontinued PLC orders**, while conducting this study we learned of several factors that confounded this result. PLC orders can be discontinued for a variety of reasons, with reasons depending in part on the role of the clinician (i.e. provider vs. VAT nurse). While VAT nurses might discontinue an order if the information entered via the CDSS does not conform to recommendations, providers also have the ability to cancel orders and can do so if there is a change in patient care plan or for inappropriate ordering. The data in this study included discontinued order data from all clinicians. Future studies should incorporate the role of the person who discontinued the order and subset the analysis based on role (i.e. VAT nurses).

Finally, with regards to exploring differences in ordering by service (A1.5), our results did not find any statistically significant differences. We limited this analysis to cardiac surgery, general surgery, and general medicine since we saw differences in these groups in the descriptive analysis. We know from findings from aim two that there may be a difference in ordering within oncology and cardiac service lines. While we used provider ID as the random effect in the model, future research could explore model service as a random effect.

In addition to effects on provider ordering behavior, the CDSS also had important impacts on education for evidence based recommendations, process efficiency, and inter-professional communication, which were identified through the qualitative study conducted for aim two, results of which were presented in chapter four. The proceeding section presents a discussion of the qualitative findings from aim two results.

Aim Two

For this aim, we sought to identify the organizational, individual, interface, and workflow factors that impact provider acceptance of this CDSS, which we defined as the willingness of

users to use the system for the task that it was designed to support,[35] and to elicit information about the impact of this system on communication between providers and the nurse-led vascular access team. Findings show that participants generally accepted the decision support that the CDSS provided. However, we found that the value of the decision support varied by provider experience level (individual) and group (organization) and that interface and system algorithm design limitations resulted in process workarounds. This system had a clear impact on inter-professional communication, with impacts again varying by provider type and group. Our finding related to provider education and work efficiency were unexpected.

Communication. Descriptions of inter-professional communication impacts varied by provider type and group (ordering provider vs. VAT nurse). Nurses characterized improvements as a result of standardizing the collection of key information from providers and increasing the structure of verbal communication with providers, whereas providers characterized improvements as a result of increased asynchronous communication of key decision making factors between teams.

With regards to standardizing the content of communication between teams, multiple studies have assessed the impact of standardized communication tools to facilitate inter-professional communication and collaboration and have reported mixed results**.** However, technology based interventions aimed explicitly at improving nurse-physician communication are limited in the literature. A study by Whitson et al. assessed the impact of a CDSS designed to guide data collection from nurses in a long-term facility setting, in preparation for telephone conversations with on-call physicians (communication direction: nurse --> physician), and found that satisfaction improved significantly in both groups. With regards to technology interventions in the acute care setting, due to the financial incentives for EHR and CDSS adoption provided by the HITECH Act,[136] there has been a steady increase in adoption of these systems and thus the literature is dominated by studies of computerized provider order entry systems (CPOE) and

CDSSs. Studies have highlighted the physician-centric design of these systems and the strict linear, unidirectional model of communication within these systems and have thus focused on the unintended consequences on nurse-provider or inter-professional communication.[137–139] A study conducted by Hoonakker et al. to evaluate the impact of a CPOE in the intensive care setting, found that that the CPOE initially had an adverse effect on communication accuracy and effectiveness between nurses and physicians, but in time returned to pre-intervention levels.[140] Several factors were identified in impacting the quality of communication, namely the reduction of face-to-face communication, which typically presents an opportunity to fill in information gaps that were not adequately communicated via electronic sources. A large qualitative study conducted in three large hospital systems found that CPOEs did not fully support the downstream work by nurses or other staff. Functionality was either lacking or insufficient information was relayed from providers to nurses.[141]

Nurse-provider communication in previous studies suffered due to the omission of essential information in the initial order, reduced opportunity for clarification either via the electronic system or in face-to-face communication, and difficulty identifying changes to the plan of care in a timely manner. In this study, although providers relied on an asynchronous communication as the primary method for information transfer, we speculate that the key to the positive impact on communication was in the interface design and workflow. Using a multi-disciplinary expert panel and a systematic review of the literature, the intervention designers identified key factors essential for venous catheter evaluation and decision making, which were then incorporated into the interface and rules engine design. This new system was then embedded into an existing, well-functioning workflow -- no change was made to the existing workflow. For patient care scenarios within the scope of the CDSS rules engine, information collected via the CDSS was deemed sufficient for the next team in the process (i.e. VAT) to efficiently perform their evaluation and carry out the orders. VAT nurses called providers after order placement;

however, the intent of this communication was to verify that no changes in the patient care plan had occurred since the time of order creation. In adhering to well-established principles for CDSS design[142] (i.e. right information, person, format, channel, at the right time in the workflow), designers were able to avoid pitfalls identified in previous studies.

From the provider perspective (physician, nurse practitioner), our study found that communication was enhanced because the CDSS allowed providers to asynchronously communicate critical information to the VAT. The key value in this type of communication in this context was the ability to communicate all critical information in a single episode, at or close to the point of care, while the patient information was in the provider's working memory.[143,144] In the absence of the CDSS, providers felt that ordering would have required multiple telephone calls between teams for ordering and clarification of information. Other studies have found that the introduction of CPOEs have resulted in increased ad-hoc communication.[145] Research has shown that interruptions can have adverse effects on task performance and cognition, depending on the nature of the task, with potential impacts to patient safety.[144,146–149] Although previously research found that the asynchronous communication adversely impacted nurse-provider communication,[137–141] in this setting, this risk of adverse effects on communication was mitigated by the workflow design. The CDSS was embedded in an existing workflow that already had a defined step for synchronous provider-nurse communication - providers were socialized to expect a follow-up telephone call for each order placed. Furthermore, providers knew in advance the content of the telephone call conversations.

In this study, the system altered communication methods by imposing structure on the information collected from providers and by increasing the amount of asynchronous communication from provider to nurse. Although VAT participants expressed satisfaction with the type of information collected by the CDSS, the system did not obviate the need for the follow up telephone call with providers. For this type of patient care scenario, synchronous

communication for each procedure order was feasible; however, this approach may not be practical for other types of scenarios, such as medication orders, due to the sheer quantity of medication orders and the number of providers entering orders per patient.[139]

Efficiency. Descriptions varied by group. VAT nurses stated that the CDSS reduced the extent of their patient chart review by providing a "snap shot" of the patient. Key information was consolidated into a single report, which allowed them to efficiently complete their review. This finding was not supported in the literature. As summarized above, studies related to the impact of CPOEs on workflow and communication showed that CPOEs did not support downstream work by nurses as information required to support downstream work was missing.[140,141] Similar to what was mentioned previously, we speculate that the key to improvements in process efficiency in this case was in the interface design and workflow and the use of a multi-disciplinary expert panel and a systematic review of the literature to identified key factors essential for venous catheter evaluation and decision making.

For patient care scenarios that fell outside of the CDSS algorithm scope, namely orders for patients with plans for discharge to a skilled nursing facility, our results found that the CDSS presented a barrier to workflow, efficiency, and communication. In these situations, providers and nurses described a work-around to the system limitations, which included entering fictitious patient data to achieve the desired recommendation and using a field intended for medication information to communicate order notes to the VAT. A 2015 meta-synthesis of qualitative research on the use of CDSS in clinical work found evidence of similar provider workarounds for instances when system recommendations were inconsistent with the patient's clinical situation.[97] However, in our study, the workaround described by the participants were unexpected given that the system allowed users to override CDSS recommendations. We attempted to understand the extent of this workaround and reviewed information entered by providers into this medication field and found little evidence of provider communication of post-acute care requirements via this

field. However, it is important to note that the aim one study time period (2012-2015) occurred before the time period in which this qualitative study was conducted (February-March 2017). Trends in discharge to post-acute care facilities may have changed since 2012-2015.

Education. Our findings related to education on evidence based recommendations were unexpected. This theme emerged when providers were asked about the value of this system in their clinical practice. Novice providers, which we defined as those with less than two years of clinical experience[150,151], described the importance of this tool in providing education for evidence-based practice and decision support. As one provider described it, "the system taught its own algorithm", with another provider stating that he felt more confident about his knowledge of specific indications as a result of using the system. Other studies have reported providers also "internalizing" CDSS algorithms after repeated use.[97] However, this finding becomes especially interesting when viewed in the context of previous exposure to this evidence base: providers stated that this topic was not addressed in medical or nursing schools and that their first exposure to this evidence was through this CDSS. This findings is another example of the impact of the exponential accumulation of biomedical and clinical information – not all topics can be taught during training.[1] The CDSS in this instance acted as a mechanism for educating providers on evidence-based practice. However, creating and maintaining CDSSs is extremely time intensive and challenging.[78,152,153] A new initiative called CDS Connect, sponsored by AHRQ, is underway to develop an infrastructure for sharing CDSSs across healthcare setting and technologies.[154] If successful, this solution has the potential to greatly reduce the CDS development lifecycle and increase the speed at which evidence can be integrated into practice. Additional research is greatly needed on ways to reduce barriers to creating and maintaining CDSS content.

Recommendation and Considerations for Future CDSS Development

Studies have identified several CDSS related features that are associated with positive outcomes.[92,93,155] Although this CDSS system contained many of the features described in the

literature, such as integration with order entry, local stakeholder involvement in design and development, integration into clinician workflow, provision of recommendations for action, and understanding system performance (done during this study), we identified potential areas for improvement, both at the technology and organizational level, that could affect system usability, data quality, workflow, and communication for future CDSSs. Recommendations outlined below are organized by intervention level and potential area of impact.

Table 3: Considerations for CDSS future design and development

Intervention levels	Area of impact & recommendations
Technology	• Data quality & usability: the following variables had missing database data and/or contained data that was difficult to analyze (e.g. user entered text): "history of mastectomy site", "double lumen reasons", and "patient requires home infusion". Regarding the mastectomy site field, we received feedback from users that the wording for this field was ambiguous, which resulted in users inappropriately using this field. With regards to the double lumen field, we speculate that a hard stop might be appropriate if management and administrators would like to track reasons for usage or further discourage usage.[77,92] Regarding the home care field, we recommend updating the algorithm to account for this scenario. • Usability: Consider expanding the order set to include ordering for vascular access catheters with potentially overlapping indication (e.g. ultrasound guided peripheral IV). Expanding the order set scope may increase user learnability, which is defined as how easy it is for users to accomplish a task the first time they encounter it, and satisfaction.[156,157] (*participant provided feedback)* • Usability: We noted in the case when the recommendation is for a peripheral IV (not a PLC or MLC), the system does not provide explicit instruction for user action. Consider updating wording to improve user learnability. [156,157] • Communication & workflow: Additional field to capture patient care requirements for all types of post-acute care services (e.g. discharge to skilled nursing facility) • Communication & workflow: Additional field for general communication between providers and the VAT.
Organizational	• All areas of impact: A plan for system monitoring and performance[155] is already in place at UPHS, which is part of the organization wide effort to implement clinical

	pathways. Common outcomes identified in the literature include length of stay, cost, patient outcomes, and provider outcomes, such as adherence to evidence based practice.[4,158] We recommend also incorporating intermediate outcomes related to system use and acceptance, as well as assessing qualitative outcomes related to communication, collaboration, and provider satisfaction as the literature has highlighted the potential negative and unintended consequence of these systems on inter-professional communication.

Study Limitations and Opportunities for Related Research

With regards to aim one, our study contained limitations that may have affected the internal and external validity of the results. This was a quasi-experimental study with no control group, conducted at a single hospital within an academic medical center. With regards to external validity, given this study design, the generalizability of these findings to other institutions may be limited. To mitigate risks related to internal validity, we used a single group pre-post analysis with longitudinal data and conducted the main statistical analysis on a group of providers that provided data in the pre and post-intervention time periods. However, the lack of a true control group prevented us from understanding the influence of any extraneous variables on the dependent variables. While we attempted to identify organizational and system wide interventions that may have impacted results, such as UPHS based education and training for evidence-based recommendations or major conferences with topics related to this area, there may have been unidentified influences that impacted our results. With regards to data, we were not able to obtain data that may have affected results, namely referral data for discharge disposition and medication data for total parenteral nutrition (a medication that requires PLC placement). Discharge referral data was not stored in a structured format within the electronic health record (Sunrise) and was therefore not stored in any of the databases maintained by the Penn Data Analytics Center. A separate database does exist with patient referral data; however, this database is not maintained by the Penn Data Analytics Center. Total parenteral medication data proved difficult to obtain

using the assigned data analytic resource. Due to the implementation of a new EHR, Epic, we were not able to obtain additional assistance for finding this data. Our study analysis and results may have been strengthened by obtaining information for PLC policies at post-acute care facilities; however, obtaining this information is challenging as it would have required the investigators to contact outside facilities. In this study, we attempted to model the change in PLC order appropriateness over time; however, obtaining this data proved to be difficult using structured data maintained by the Penn Data Analytics Center.

With regards to aim two, our study was implemented in a single hospital, in a single service line (general medicine), thus our findings may not be generalizable to other services within the hospital or other settings. Our original study design had included observation of providers as they interacted with the system in their natural environment (observation and contextual inquiry) and observation of VAT RNs as they reviewed PLC and MLC orders. Our original plan was to conduct a minimum of 4 observations and contextual inquiry sessions, with additional sessions conducted as needed. PLC and MLC orders are rare events within the general medicine service; we were not able to find opportunities for observation and contextual inquiry before the implementation of the new electronic health record system (Epic). Findings from this part of the study would have enriched study results by (1) adding details that were not captured in interviews; (2) allowing us to gain an understanding of the social and physical environment; and (3) providing an opportunity for participants to express opinions that were maybe difficult to express during a formal interview. This approach also would have allowed the investigators to validate or expand on insights obtained during interviews. Regarding thematic saturation, while our sample size was sufficient to achieve saturation, in analyzing the data, we did find differences between providers. Future research should focus on understanding the differential value of CDSSs by provider level and type.

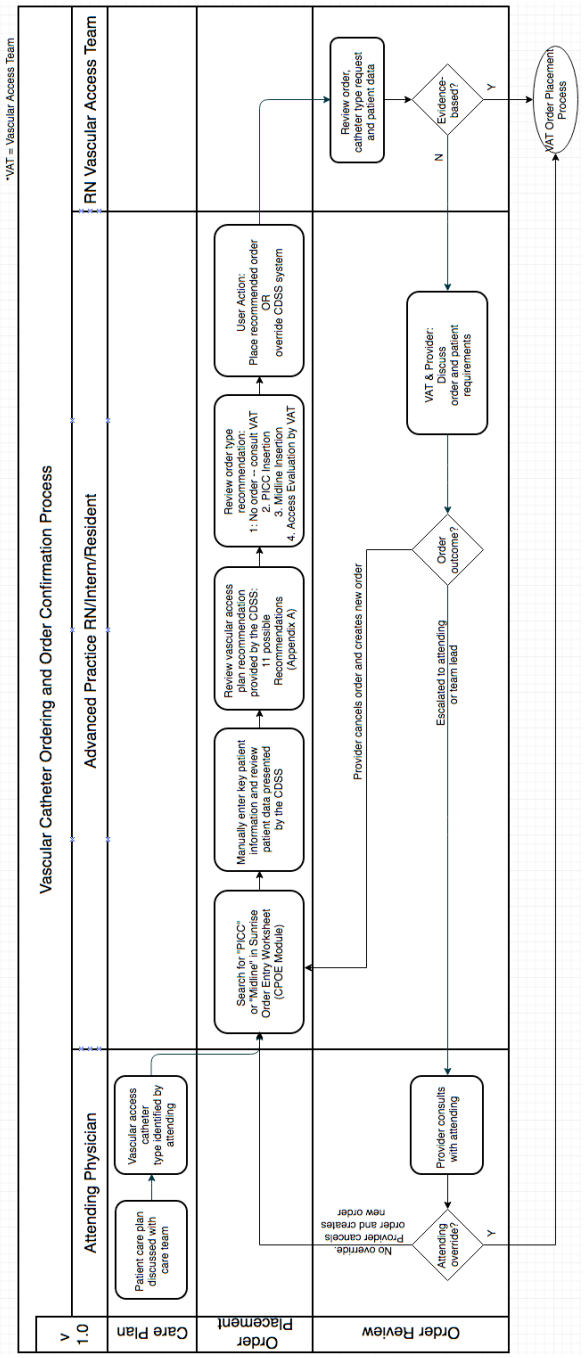
Future Research Opportunities

Related to this evidence-based topic, in addition to the opportunities mentioned in the previous section, we recommend a randomized trial to identify the impact of a CDSS on provider PLC ordering, when a vascular access team is not in place. In addition, as our understanding of catheter use patterns and prevalence in post-acute care facilities is limited, future research should also include conducting studies to understand use, prevalence, and patient outcomes.

General CDSS research opportunities include conducting studies to understand the feasibility of using a repository for shareable CDSS logic and the impact of this intervention on CDSS adoption rates at various care setting and types, including community hospital, clinics, post-acute care facilities as well as academic medical centers. Future research should also identify factors that are related to CDSS utility and use (e.g. previous exposure to evidence, clinician experience) and also development of tools to help system implementers identify the types of healthcare decisions that are likely to be best supported by CDSSs.

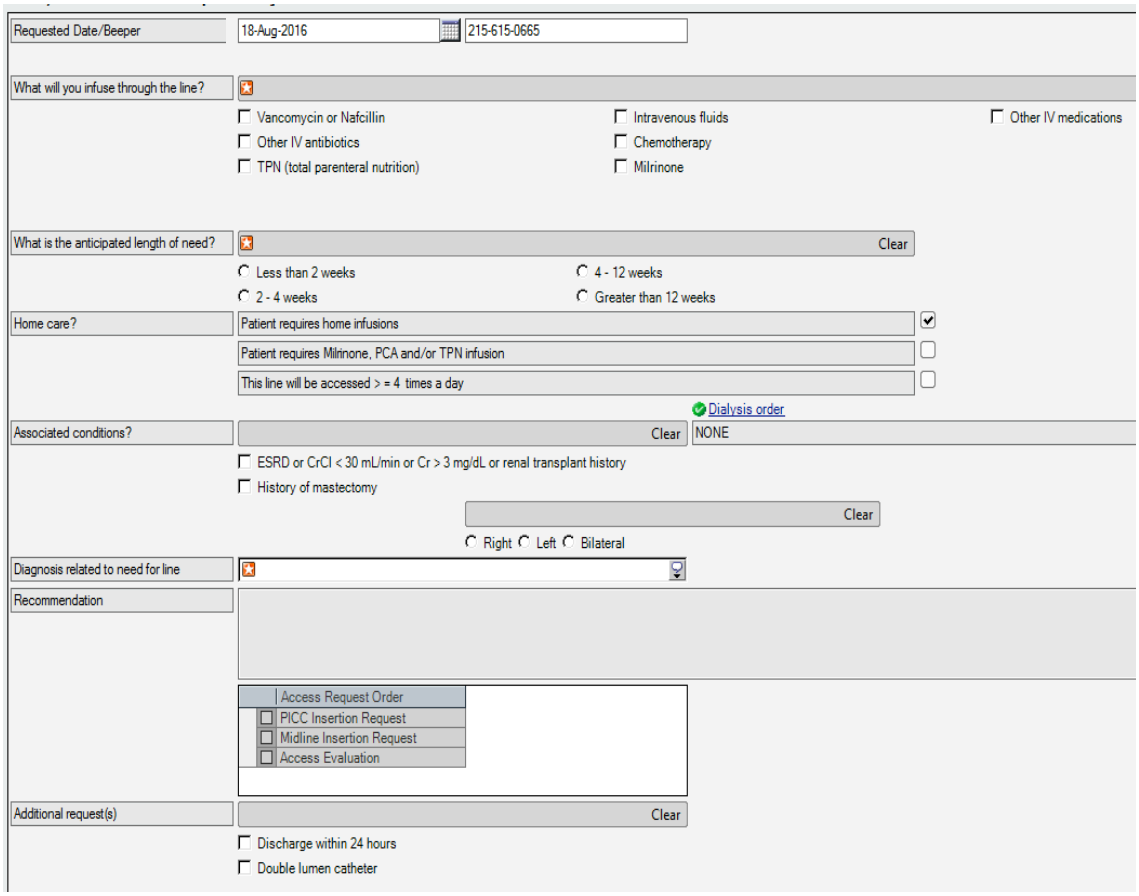
APPENDICES

Appendix A: Venous Catheter Ordering Process Overview



Appendix B: Clinical Decision Support System User Interface

CDSS Feature	V1	V2
Medication Type	✓	
Treatment Duration	✓	
Associated Conditions	✓	
Diagnosis related to line need	✓	
Catheter Recommendations	✓	
Order Type (Default)	✓	
Double Lumen	✓	
Home Care Infusion		✓
Discharge w/i 24 hours		✓
Improved wording for order recommendation		✓
Field Auto-Population		✓
Double lumen default		✓



Appendix C: Mapping of Conceptual Model Components to CFIR

Socio-technical Model Components	CFIR Model Constructs and Sub-constructs
Human-computer interface (A) components involve how users interact with the application	**Intervention characteristics (I):** **Design Quality & Packaging** Perceived excellence in how the intervention is bundled, presented, and assembled. **Complexity:** Perceived difficulty of implementation, reflected by duration, scope, radicalness, disruptiveness, centrality, and intricacy and number of steps required to implement.
Workflow and communication (B) involve processes that users follow in the course of patient care.	*No direct mapping with CFIR*
***People or personnel* (C)** refers to all the different roles and teams that interact with the system.	**Characteristics of individuals (IV):** Knowledge & Beliefs about the Intervention: Individuals' attitudes toward and value placed on the intervention as well as familiarity with facts, truths, and principles related to the intervention. **Individual Identification with Organization:** A broad construct related to how individuals perceive the organization, and their relationship and degree of commitment with that organization. **Self-Efficacy:** Individual belief in their own capabilities to execute courses of action to achieve implementation goals.
***Clinical content* (D)** refers to the rules, text, and representation of clinical care in the application.	**Intervention characteristics (I):** **Evidence Quality and Strength:** Stakeholders' perceptions of the quality and validity of evidence supporting the belief that the intervention will have desired outcomes.
***Internal organization* (E)** include policies, procedures, and culture that influence use of the tool.	**Inner setting (III):** **Structural Characteristics:** The social architecture, age, maturity, and size of an organization. **Learning Climate:** A climate in which: a) leaders

express their own fallibility and need for team members' assistance and input; b) team members feel that they are essential, valued, and knowledgeable partners in the change process; c) individuals feel psychologically safe to try new methods; and d) there is sufficient time and space for reflective thinking and evaluation.

Access to Knowledge & Information: Ease of access to digestible information and knowledge about the intervention and how to incorporate it into work tasks.

Appendix D: 2 X 2 table for construction of the MLC concordance variable

		CDSS Recommendation	
Provider Order		**MLC**	**PLC**
	MLC	Concordance	Disagreement
	PLC	Disagreement	Concordance

MLC concordance = Concordance

if CDSS recommendation = MLC & provider order = MLC

MLC concordance = Disagreement

if CDSS recommendation = MLC & provider order = PLC

$$\textbf{Proportion MLC Concordance} = \frac{\text{Number of orders with MLC condordance}}{\text{Total MLCs recommended}}$$

Appendix E: Aim Two Interview Guide

"Hi, I first want to thank you for agreeing to talk to me about your experiences with the vascular access decision support system. I want you to know that everything you say is strictly confidential – I will never share your name or mention the unit with anyone. "

Demographic data and background data

- Gender

1. Can you tell me
    a. Your years of service: for NPs, years of service before MSN
    b. Degrees obtained,

Exploring participants experience with the Vascular Access CDSS and eliciting information about interface design *(Model Construct A, E)*

2. How often do you use the vascular Access CDSS in your role? Daily, weekly, rarely.
3. Can you tell me about any training you may have received prior to using this system?
    a. Did you feel that the training adequately prepared you to use the system?
        i. If NO: can you elaborate on why not?
4. How many systems do you need to reference in order to complete a request?
5. Please describe the "pain points" in using this vascular access CDSS?
6. Are there additional patient factors that the tool should be taking into consideration?

CDSS Content/Evidenced Based Practice *(Model Construct D)*

7. Do you think the tool's recommendations are in-line with current evidenced based practice for PICC and Midline use?
    a. If NO: can you provide an example?
8. Are there patient factors that the tool should be taking into consideration?

Workflow, Communication, and Organizational/Specialty Culture *(Model Construct B, C, F)*

9. Can you describe the process for requesting vascular access device?
    a. How do you view your role in this process?
    b. How are decisions made regarding the type of vascular access device to order?
    c. How do you reconcile differences between what the tool recommends and your clinical judgement?
10. How well does the CDSS fit with existing work processes and practices in your setting?
11. What are some of the challenges or barriers to using this CDSS for vascular access requests?
    a. ***Prompts if no response*:**
        a. I've heard about "gaming" the tool – what does this mean to you?
        b. Have you ever "gamed" the tool?
            i. If so, can you tell me about an instance where you needed to do this?
12. Are there cases when the CDSS is not used to request vascular access placement?
        a. If Yes:
            1) Can you tell me about situations where you've seen this?

2) About how often does this occur?

13. What **value** does the CDSS provide to you?
    a. Can you think of any direct benefits to your <u>patient</u>?
14. Is there a strong need for this intervention?
    a. Why or why not?
    b. Do others see a need for the intervention?
15. Are you able to act on the recommendations provided by the system if they are not aligned with the plan of care agreed upon during rounds?
    a. What gives you that level of confidence (or lack of confidence)?
16. How has this tool improved or hindered **communication** between you and the other team (e.g. VAT if participant is a provider)?

Additional questions for VAT RN participants

17. Can you describe the process for **reviewing and approving** a vascular access device request? ***<u>(Model Construct B, C, E)</u>***
    a) How do you view your **role** in this process?
    b) How do **you decide on the most appropriate catheter** for the patient?
        a. ***After response***: Do you know if a hospital policy/procedure exists.
            i. If so,
                1. how often do you reference this document?
                2. Where is it stored?
    c) Can you describe any issues or challenges you experience with the process?
        a. ***Prompts if no response*:**
            i. What is your course of action when there is a mismatch between tool recommendations and hospital policy?
    d) How are **"urgent/stat"** request processed?
    e) How are **after-hours** request processed?
18. Can you tell me about your confidence in the **accuracy and quality** of the data entered by providers? ***<u>(Model Construct B)</u>***

The following prompts may be used for further probing:

A. Would you give me an example?
B. Can you elaborate on that idea?
C. Would you explain that further?
D. I'm not sure I understand what you're saying...
E. Is there anything else?

Appendix F: Table 1A – All Inpatient Admissions

	Overall	Period 1	Period 2	Period 3
Admitted patients (%)	60,479	21,274 (35.18)	17,691 (29.25)	21,418 (35.41)
Age: >=65	16819 (27.82)	4078 (19.18)	5737 (32.45)	6986 (32.64)
Sex, female	35364 (58.47)	12506 (58.79)	10295 (58.19)	12514 (58.43)
Race (%)				
White	31703 (52.42)	10633 (49.98)	9452 (53.43)	11570 (54.02)
Black	22348 (36.95)	8578 (40.32)	6280 (35.50)	7450 (34.78)
Asian	1665 (2.75)	593 (2.79)	467 (2.64)	603 (2.82)
Unknown	4763 (7.88)	1470 (6.91)	1492 (8.44)	1795 (8.38)
Service Specialty Groups: *top 5, (%)*				
Surgery	33,612 (55.56)	12,232 (57.50)	9,863 (55.75)	11,463 (53.48)
General Medicine	14,136 (23.37)	5,072 (23.84)	4,098 (23.16)	4,942 (23.06)
Cardiovascular	4,419 (7.30)	1,555 (7.31)	1,338 (7.56)	1,521 (7.10)
Oncology	3,372 (5.57)	1,192 (5.60)	992 (5.61)	1,182 (5.51)
Cardiac Surgery	3,205 (5.30)	854 (4.01)	982 (5.55)	1,364 (6.36)
Patient Acuity				
	Overall	**Period 1**	**Period 2**	**Period 3**
APR-DRG Weight				
Mean (SD)	1.73 (2.28)	1.64 (2.22)	1.75 (2.28)	1.80 (2.33)
Median (IQR)	1.01 (0.59, 1.86)	0.96 (0.57, 1.69)	1.02 (0.60, 1.96)	1.04 (0.59, 1.97)
DX per patient				
Mean (SD)	16.08 (11.09)	14.03 (9.74)	16.32 (10.88)	17.50 (11.96)
Median (IQR)	13 (8, 21)	11 (7, 18)	14 (8, 22)	14 (9, 23)
Creatinine Clearance: n (%) less than 30 *(indication of end stage renal disease)*				
Mean	3,397 (5.62)	1091 (5.13)	1101 (6.22)	1198 (5.59)
Median	3261 (5.39)	1040 (4.89)	1057 (5.97)	1158 (5.41)
Length of Stay				
Mean (SD)	5.95 (9.11)	5.54 (9.29)	6.08 (8.34)	6.24 (9.49)
Median (IQR)	3 (2, 6)	3 (2, 6)	3 (2, 7)	3 (2, 7)
ICU care (%)	4,652 (7.69)	1,526 (7.17)	1,402 (7.92)	1,716 (8.01)
Intravenous Medications				
	Overall	**Period 1**	**Period 2**	**Period 3**
Medications per encounter, n				
Mean (SD)	5.11 (5.23)	5.01 (5.17)	5.22 (5.25)	5.11 (5.25)
Median (IQR)	3 (2, 6)	3 (2, 6)	4 (2, 6)	3 (2, 6)
Medication administrations per encounter, n				
Mean (SD)	12.92 (19.96)	13.08 (20.38)	13.15 (19.88)	12.54 (19.53)
Median (IQR)	6 (3, 14)	6 (3, 15)	7 (3, 15)	6 (3, 14)
Medications administered by category, n (%)				
Category medications administered, n (%)				
Vancomycin	10569 (20.05)	3418 (18.33)	3211 (20.58)	3920 (21.34)
Other antibiotics	30886 (58.61)	10774 (57.77)	9215 (59.07)	10843 (59.04)
Milrinone	957 (1.82)	283 (1.52)	317 (2.03)	355 (1.93)
Chemotherapy	2016 (3.83)	740 (3.97)	568 (3.64)	705 (3.84)
Other IV Meds	38465 (72.99)	13641 (73.14)	11540 (73.97)	13213 (71.95)
Patient Controlled Analgesia	12760 (24.21)	4768 (25.57)	3802 (24.37)	4171 (22.71)
Patients who received , n (%)				
Only 1 med	8863 (16.82)	3310 (17.75)	2470 (15.83)	3072 (16.73)
> one med	43838 (83.18)	15340 (82.25)	13131 (84.17)	15293 (83.27)

Discharge Diagnoses (ICD 9)	
	Overall
Diagnosis: *Top 5, (%)*	
Intestinal obstruction (560.0)	6485 (11.06)
Acute appendicitis (540.0)	2879 (4.91)
Malignant neoplasm of nipple and areola (175.0)	1462 (2.49)
Ankylosing Spondylitis (720.0)	1375 (2.34)
Malignant neoplasm of parietal pleura (163.0)	1260 (2.15)

Appendix G: Table 1B – Patients with Catheter Order(s)

	Overall	Period 1	Period 2	Period 3
Admitted patients with orders (%)	7391 (12.22% of overall patient admissions)	2901 (39.25)	2175 (29.43)	2291 (30.99)
Age: >=65	2656 (35.94)	750 (25.85)	915 (42.07)	985 (42.99)
Sex, female	3445 (46.61)	1345 (46.36)	1021 (46.94)	1069 (46.66)
Race				
White	4616 (62.45)	1715 (59.12)	1406 (64.64)	1480 (64.60)
Black	1954 (26.44)	914 (31.51)	504 (23.17)	528 (23.05)
Asian	141 (1.91)	56 (1.93)	41 (1.89)	44 (1.92)
Other	677 (9.16)	216 (7.44)	224 (10.30)	239 (10.43)
Service Specialty Groups: *top 5*				
Surgery	2616 (35.39)	1030 (35.50)	832 (38.25)	744 (32.47)
General Medicine	2009 (27.18)	867 (29.89)	557 (25.61)	578 (25.23)
Oncology	1176 (15.91)	485 (16.72)	336 (15.45)	351 (15.32)
Cardiac Surgery	936 (12.66)	265 (9.13)	274 (12.60)	396 (17.29)
Cardiovascular	591 (8.0)	244 (8.41)	163 (7.49)	182 (7.94)
Patient Acuity				
	Overall	**Period 1**	**Period 2**	**Period 3**
APR-DRG Weight				
Mean (SD)	3.74 (4.02)	3.41 (3.41)	3.72 (3.95)	4.19 (4.18)
Median (IQR)	2.21 (1.10, 5.24)	1.91 (1.01, 4.04)	2.24 (1.10, 5.17)	2.75 (1.24, 5.81)
DX per patient				
Mean (SD)	24.57 (13.73)	21.56 (12.29)	24.35 (13.01)	27.56 (14.94)
Median (IQR)	22 (15, 32)	19 (12, 28)	23 (15, 31)	24 (17, 35)
Creatinine Clearance: n (%) less than 30 *(indication of end stage renal disease)*				
Mean	435 (5.89)	168 (5.79)	145 (6.67)	121 (5.28)
Median	406 (5.49)	153 (5.27)	136 (6.25)	116 (5.07)
Length of Stay				
Mean (SD)	15.67 (18.69)	13.95 (20.07)	16.04 (16.16)	17.50 (18.96)
Median (IQR)	10 (5, 20)	8 (5, 18)	11 (6, 21)	12 (7,22)
ICU care (%)	448 (10.77)	312 (10.74)	215 (9.89)	400 (11.57)
Intravenous Medications				
	Overall	**Period 1**	**Period 2**	**Period 3**
Medications per encounter, n				
Mean (SD)	10.56 (8.39)	9.87 (8.31)	10.66 (8.34)	11.31 (8.42)
Median (IQR)	8 (4, 15)	7 (4, 13)	9 (4, 14)	9 (5, 16)
Medication administrations per encounter, n				
Mean (SD)	33.42 (22)	32.10(20)	33.37 (23)	34.95 (24)
Median (IQR)	22 (9, 45)	20 (8, 43)	23 (10, 46)	24 (11, 46)
Medications administered by category, n (%)				
Vancomycin	3623 (50.67)	1266 (45.49)	1079 (51.02)	1267 (56.82)
Other antibiotics	5473 (76.55)	2039 (73.27)	1644 (77.73)	1772 (79.46)
Milrinone	483 (6.76)	159 (5.71)	144 (6.81)	179 (8.03)
Chemotherapy	982 (13.73)	393 (14.12)	272 (12.86)	316 (14.17)
Other IV Meds	6273 (87.73)	2397 (86.13)	1860 (87.94)	1995 (89.46)
Patient Controlled Analgesia	1963 (27.45)	780 (28.03)	585 (27.66)	590 (26.46)
Patients who received , n (%)				
Only one IV med	368 (5.15)	176 (6.32)	110 (5.20)	81 (3.63)
>one med	6782 (94.85)	2607 (93.68)	2005 (94.80)	2149 (96.37)

Discharge Diagnoses (ICD 9)	
	Overall
Diagnosis: *Top 5, (%)*	
Malignant neoplasm of parietal pleura (163.0)	340 (4.67)
Ankylosing Spondylitis (720.0)	304 (4.17)
Dermatitis due to substances taken internally (693.0)	236 (3.24)
Benign neoplasm of other female genital organs (221.0)	230 (3.24)
Erythematosquamous dermatosis (191.0)	209 (2.87)

Appendix H: Analysis of orders over time (A1.1 – A1.3)

Outcome 1: Proportion of PLC orders (A1.1)

Estimated proportion of PLC orders per period

Period	Expected Value	Period Comparison	p-value (period compared to base)
1	0.62	1 & 2	0.86
2	0.62	1 & 3	0.04
3	0.59	2 & 3	0.36

Segmented linear regression model: separate slopes calculated for each period

Period	Slope of the line in each period	Period (pre/post only)	Slope of the line in each period
1	0.006	1	0.006
2	-0.002	2	-0.003
3	-0.003		

Outcome 2: Proportion of discontinued PLC orders (A1.2)

Estimated proportion of discontinued PLC orders per period

Period	Expected Value	Period Comparison	p-value (period compared to base)
1	0.48	1 & 2	0.66
2	0.47	1 & 3	0.50
3	0.46	2 & 3	0.70

Segmented linear regression model: separate slopes calculated for each period

Period	Slope of the line in each period	Period (pre/post only)	Slope of the line in each period
1	0.01	1	0.01
2	0.002	2	0.0006
3	0.004		

Outcome 3: Proportion of double lumen PLC orders (A1.3)

Estimated proportion of double lumen PLC orders per period

Period	Expected Value	Period Comparison	p-value (period compared to base)
1	0.56	1 & 2	<0.001
2	0.31	1 & 3	<0.001
3	0.33	2 & 3	0.398

Segmented linear regression model: separate slopes calculated for each period

Period	Slope of the line in each period	Period (pre/post only)	Slope of the line in each period
1	-0.001	1	-0.001
2	-0.03	2	-0.0003
3	-0.001		

Appendix I: Variance component models: Covariates & results of bivariate analysis

*Each variable listed in the below tables is defined at the provider level. For example, LOS is the mean LOS for patients for a given provider. Medications: mean number IV meds is the mean number of IV meds for patients for a given provider.

Proportion of PLC Orders (A1.1)

	Full dataset		Limited dataset (457)	
Variable	**Bivariate Analysis**	**Covariates in final model**	**Bivariate Analysis**	**Covariates in final model**
APR-DRG Weight (median)	0.8541		0.7375	
Age: Proportion per provider > 65	0.0899		0.1347	
Service: Proportion Cardiac Surgery	0.0735		0.2049	
Service: Proportion Surgery	<.0001	<.0001	<.0001	<.0001
Service: Proportion Medicine	<.0001	<.0001	0.0003	<.0001
CrCl: Proportion of patients < 30 (median)	0.0078		0.9259	
CrCl: Proportion of patients < 30 (mean)	0.0045	0.0206	0.7542	
LOS (mean)	0.2571		0.8752	
LOS (Median)	0.0212		0.0314	
Medications: Mean number IV meds	<.0001		0.0259	
Medications: Mean number of IV med administrations	0.0003		0.0553	
Medications: Proportion of patients administered chemo	<.0001	<.0001	<.0001	<.0001
Medications: Proportion of patients administered vancomycin / nafcilin	<.0001	<.0001	0.0003	<.0001
Medications: Proportion of patients administered milrinone	0.6297		0.5403	
Medications: Proportion of patients administered IV fluid	<.0001		0.0007	
Medications: Proportion of patients administered other antibiotics (not vanco)	0.0861		0.8143	

Proportion of double lumen PLC orders (A1.3)

	Full dataset		Limited dataset (457)	
Variable	Bivariate Analysis	Covariates in final model	Bivariate Analysis	Covariates in final model
APR-DRG (median)	0.0023	0.0294	0.0036	
Age: proportion per provider > 65	0.0999		0.2331	
Service: Cardiac Surgery	0.4229		0.3530	
Service: Surgery	0.0537		0.6051	
Service Medicine	<.0001	<.0001	<.0001	<.0001
CrCl: Proportion of patients < 30 (median)	0.8710		0.7459	
CrCl: Proportion of patients < 30 (mean)	0.6348		0.3977	
LOS (mean)	0.0082		0.0010	
LOS (Median)	0.0144*	0.0261	0.0003*	
Medications: Mean number IV meds	<.0001	<.0001	<.0001	<.0001
Medications: Mean number of IV med administrations	<.0001		<.0001	
Medications: Proportion of patients administered chemo.	<.0001	0.0047	<.0001	0.0028
Medications: Proportion of patients administered vancomycin/ nafcillin	0.0405	<.0001	0.6174	
Medications: Proportion of patients administered milrinone	0.1679		0.9111	
Medications: Proportion of patients administered IV fluid	<.0001	0.0483	0.0271	
Medications: Proportion of patients administered other antibiotics (not vancomycin)	0.4417		0.3090	

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