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Final Progress Report
Engineering Highly Reliable Communication and Coordination Systems for High-Risk Patients, Referrals, and Tests

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Structured Abstract
Purpose: The Engineering High-Reliability Learning Lab (EHRLL) worked with four Harvard-affiliated primary care practices to enhance capacity for innovation and develop highly reliable systems that address communication and coordination challenges at the intersection of primary and specialty care that pose safety risks for patients with complex conditions.

Scope: Project teams sought to engineer systems to improve high-priority primary to specialty external referrals (Project 1); perioperative care of children undergoing spinal fusion for scoliosis (Project 2); opioid medication management (Project 3); and home health management following hospital discharge (Project 4).

Methods: Each project involved multidisciplinary R&D teams that met weekly or biweekly to pursue AHRQ's systems engineering cycle---problem analysis, design, development, implementation, and evaluation---by applying system engineering methods. Project teams participated in 13 Learning Sessions, held approximately every 4 months, to share learnings and introduce new tools and concepts. Teams completed "storyboard" presentations for each Learning Session and "EHRLL transformation reflections" between them. EHRLL evaluation combined quantitative assessment with qualitative and survey methods.

Results: Team progress applying engineering methods and achieving results was variable. Our meta-analysis derived a constraint management process, demonstrating how R&D teams experience and overcome constraints to maintain momentum on projects; identified elements of an effective learning ecosystem, which requires interpersonal/interprofessional, structural, informational, and process alignment; and showed how patients' roles change from informant, to partner, to active change agent throughout projects' lifecycles through social identification processes. Participant evaluations of the learning lab and team progress suggested satisfaction with the lab, their team's progress, and their own learning.

Key Words: patient safety, systems engineering, learning laboratory, organizational learning

Purpose (Objectives of the study)

The Engineering High-Reliability Learning Lab (EHRLL) worked with four Harvard-affiliated primary care practices to establish a learning laboratory to enhance capacity for innovation and to develop highly reliable systems that address communication and coordination challenges at the intersection of primary care and specialty practices that pose patient safety risks.

Our specific aims were:

Aim 1: To build a re-engineering and shared learning infrastructure that comprises an Administrative/Learning Core, an Engineering Core, multidisciplinary teams composed of investigators, engineers with expertise in healthcare challenges, and "Disruptors" (a cadre of innovators and experts from disciplines and industries outside of healthcare); and that stimulates a systematic approach for identifying, designing, developing, spreading, and evaluating patient safety innovations.

Aim 2: To engage in research projects that will apply systems engineering and operations management theory and methods to the development of innovative, cross-disciplinary team-based solutions for improving Health Information Technology (HIT)-supported processes for high-risk patients, referrals, and tests and designing highly reliable systems that are generalizable.

Aim 3: To implement and spread redesigned systems across a range of hospital/community-based primary care practices and to test systems' generalizability in alternative settings and with other medical conditions.

Aim 4: To assess the impact of redesigned systems on practice, team, provider, and patient outcomes, and disseminate findings as well as tools and resources to support national replication, as appropriate.

Scope (Background, context, settings, participants, incidence, prevalence)

Patient Safety Problems. Although select achievements in patient safety have been impressive, successes have often addressed egregious and amenable threats in individual, uniquely positioned institutions.[1]

In contrast, consistently providing safe and high-quality healthcare presents complex problems that demand systems-level approaches and cooperation among multiple disciplines.[2–4] Ensuring appropriate subspecialty input to evaluate concerning symptoms and management, early detection of disease based on risk profiles and symptoms, care integration and tracking for patients at high risk based on new problems or exacerbations of underlying comorbidities, and coordinating and ensuring timely care for patients with medical complexity are difficult under the best circumstances.[5–7] Reliably accomplishing these tasks is challenged further when treating patients whose risk profiles predispose them to serious conditions or complexity associated with low socioeconomic status or comorbid conditions.[8–11] Addressing such complex problems often requires breaking them down into manageable components that can be examined from multiple perspectives, standardized, and made more reliable, then reintegrated to form complete systems of care.

Patient Safety at the Intersection of Primary and Specialty Care. Relative to inpatient care, less is known, and approaches for mitigating harm are less well developed in the primary care setting,[12,13] despite the fact that most care is delivered there.[14–18] The ambulatory setting is rife with error-prone processes, and chief among these are those that require communication and coordination between primary and specialty providers.[16,19–26] Outpatient errors are less likely to be caught due to a common lack of safeguards in inpatient settings and a tendency to employ less redundancy in the form of processes to double check the accuracy and appropriateness of information, decisions, or actions. Both risk management and regulatory oversight are also less developed in primary care.[27] Innovative initiatives that incorporate systems principles and engage design and engineering disciplines are needed to address seemingly intractable challenges at the intersection of primary and specialty care, specifically those that relate to high-risk patients, referrals, and tests.[2,28]

Engineering Highly Reliable Communication and Coordination Systems. Healthcare organizations are increasingly adopting multiorganizational collaborative approaches to quality improvement[29–31] and recognizing that changes in performance require changes in systems.[32] To be effective, we must go beyond traditional collaboratives to explicitly stretch professional boundaries, envision bold design innovations, and take advantage of brainstorming and rapid prototyping techniques common in other leading-edge sectors of the economy. Promising new integrated systems must be refined through multiple develop-test-revise iterations as occur in system engineering projects[33] and then tested in actual clinical settings. Despite widespread endorsement of approaches that incorporate multidisciplinary perspectives and systems thinking,[2] few initiatives follow these principles to realize new insights and robust approaches to address patient safety problems.[34] EHRLL was positioned to do so. Prior research of co-investigators had demonstrated deep familiarity and experience with these approaches. Dr. Singer and colleagues drew extensively on lessons from high-reliability organizations in measuring the impact of the Patient Safety Consortium.[35,36] Both the Academic Innovations Collaborative/Comprehensive, Accessible, Reliable, Exceptional and Safe (AIC/CARES) initiative[37] and PROMISES use reliability science and lean management approaches for increasing reliability for error-prone processes in primary care practices.[26,37] Dr. Benneyan was and is a leading authority on healthcare systems engineering and founding director of the Healthcare Systems Engineering Institute, which focuses on improving healthcare efficiency, quality, logistics, safety, flow, effectiveness, and access through the application of systems engineering methods. Through his guidance as director of EHRLL's Engineering (Engine) Core, we sought to apply these and more advanced approaches to interrelated problems facing EHRLL Re-engineering and Design (R&D) Teams (primary to specialty referrals, complex perioperative care, opioid medication management, and home health management) in an integrated way to enhance the overall safety of systems of care for patients.

Building EHRLL on Two Highly Successful Innovation Programs. EHRLL built on and combined two successful, demonstrated activities: (1) Harvard's AIC/CARES learning collaborative, and (2) Northeastern's healthcare systems engineering CMS healthcare regional extension center (CMS/CMMI funded) for deploying systems engineering approaches (engineering teams/dyads embedded in multiple interdisciplinary teams, applying standard toolkit of systems engineering methods, etc. The AIC/CARES initiative was formed in 2012 with 28 Harvard-affiliated adult and pediatric primary care practices. AIC/CARES was a joint effort of the Harvard Medical School (HMS) Center for Primary Care and seven healthcare systems, each linked to a Harvard-affiliated academic medical center.[37] EHRLL R&D teams were based at systems that had participated in AIC/CARES (Atrius Health, Boston Children's Hospital, Brigham and Women's Hospital, Mount Auburn Hospital). The 19 EHRLL practices and affiliates comprised 500+ physicians and 1500+ staff members serving more than 260,000 patients.

All practices use electronic medical records to record patient histories, order tests and prescriptions, view results, place referrals, and create registries. Their affiliated health systems have a significant proportion of their patients under shared risk contracts with payers. The clinical and administrative leadership within the practices, and the corresponding health systems up to the Chief Executive Officer, were engaged. EHRLL leveraged AIC/CARES' ecosystem, progress, and momentum and added a supportive learning and reengineering infrastructure. The Regional Extension Center worked with 87 health systems across the US to use SE methods to improve safety, flow, access, and outcomes across a range of inpatient and ambulatory problems. EHRLL leveraged the Regional Extension Center's approach to systems engineering-driven innovation.

Focus on Four Patient Populations at Risk for Diagnostic Errors and Delayed Treatment. Each of our research projects sought to apply techniques from the systems engineering and operations management literature to help frontline practitioners develop innovative solutions for vexing ambulatory patient safety challenges, which can lead to preventable errors in diagnosis and patient management.[38,39]

Project 1. Engineering Highly Reliable Closed Loop Systems for High-Priority Primary to Specialty Referrals (P1 Primary to Specialty Referrals) worked to design and develop a robust and reliable system for integrated, coordinated, patient-centered, closed-loop management of high-priority primary to specialty care referrals to reduce harm caused by missed or delayed treatment and to reduce the overall cost of care. Our Project 1 was phased out in Year 4 due to competing organizational priorities and replaced by a new project, Project 4.

Project 2. Engineering Highly Reliable Coordination Systems for Children with Medical Complexity Undergoing Surgery (P2 Complex Perioperative Care) worked to design and develop a robust and reliable system for coordinating perioperative care with high potential to reduce toward zero the risk of harm of children with medical complexity undergoing costly, high-risk orthopedic surgery, (i.e., spinal fusion for scoliosis).

Project 3. Engineering a Highly Reliable System for Managing Opioid Medication Management Processes for Adults with Complex Care Needs (P3 Complex Opioid Medication Management) sought to design and develop a robust and reliable opioid medication management system for managing new or exacerbated conditions in patients with complex care needs to reduce harm caused by overuse of opioid medication and to reduce the overall cost of care.

Project 4. Engineering a Highly Reliable Communication and Coordination System between Primary and Home Health Care for Adults with Complex Care Needs (P4 Complex Home Health Management) sought to design and develop a robust and reliable system for managing home health management for patients at greatest risk of readmission following hospital discharge and to reduce the overall cost of care.

Though patients' needs differ based on their risk profiles and causes of complexity, the premise underlying EHRLL was that sufficient similarities exist that the simultaneous development of innovations across projects would spark synergies with high potential to enhance creativity and impact. For example, across all projects, HIT innovation linked teams of providers to patients for task management and identification of shared priorities. Across all projects, linkages were required between primary care and specialty practices. And all projects shared a commitment to including patients and caregivers as an essential part of the design team.

EHRLL sought to redesign highly reliable systems that leverage HIT and high-functioning care teams to create highly reliable workflows for managing high-risk specialist referrals, integrating and tracking care, and improving communication and coordination among primary and specialty providers and between providers, patients, and family members, which, in turn, lead to more accurate and expedited diagnoses and disease management. We emphasized patient/family partnership in problem analysis, for identifying solutions, and as key participants in re-engineered workflows. Although patients have different needs based on their risk profiles and causes of overall complexity, sufficient similarities exist that the simultaneous development of innovations across projects provide synergies were expected to enhance creativity and potential impact for both. EHRLL presented an unprecedented opportunity to enhance the overall safety of the system of care and for important patient populations at risk for harm.

Methods (Study design, data sources/collection, interventions, measures, limitations)

We describe methods pertaining to projects, cross-project activities, and training and professional development separately.

Project Activities

Each of EHRLL's four projects formed an R&D team that included clinicians and non-clinicians from the health system, embedded engineers from our Engineering (Engine) Core, Administration (Admin) Core members, and patient partners. Though disrupted to varying degrees by COVID-19, each of the R&D teams held weekly or biweekly team meetings at which members gathered face to face or by teleconference/webinar to work through project aims following roughly the innovation cycle recommended by AHRQ and specific recommendations for operationalizing stages of the cycle provided at each EHRLL Learning Session (described below). In general, teams engaged in problem analysis, design, development, implementation, and evaluation. The teams moved beyond initial problem analysis, engaged in design and development, and implemented and evaluated to different degrees. In doing so, they applied system engineering methods best suited to their projects to design, spread, and sustain solutions to the problems they aimed to address.

Project 1 aimed to close external referral loops between primary and specialty providers. Its R&D team performed an assessment of the strengths/weaknesses of current frameworks and prototyped a redesigned system for urgent referrals using a lean/rapid improvement event.

Project 2 aimed to install and sustain a reliable pathway of integrated, comprehensive perioperative care for children with medical complexity. The R&D team used systems engineering tools including process mapping, contrast analysis, failure modes and effects analysis, safety-2, and FRAM diagramming, combined with semi-structured interviews of parents and children and clinicians from surgery, anesthesia, general pediatrics, hospital medicine, intensive care, specialty care, and rehabilitation, to analyze the problem.

Project 3 aimed to improve the safety and efficiency of opioid prescribing in primary care starting. The team mapped its workflows, performed failure modes and effects analysis, and surveyed providers to identify opportunities for redesign.

Project 4 aimed to reduce hospital readmissions and improve health outcomes and quality of life for high-risk patients transitioning from hospital to home care. After joining EHRLL in Year 2, the R&D team used swim lane diagrams, metrics definition, an extended failure modes and effects analysis, and contrast analysis to analyze problems with their discharge process.

Cross-Project Activities

The EHRLL administrative core met weekly and the full leadership team meets biweekly to review project progress and next steps and to discuss programmatic topics, such as planning for upcoming Learning Sessions and evaluation activity administration and results.

We conducted 13 EHRLL-wide Learning Sessions. These project-wide half-day learning sessions occurred every 4 months (with the exception of our March 2020 learning session, which we cancelled due to COVID-19), bringing together the R&D teams from all four EHRLL projects to share learnings and to introduce new systems engineering methods or concepts. Each Learning Session also included hands-on opportunities for teams to apply newly introduced tools, brainstorm within teams about next steps, and discuss, across teams, information about project progress and lessons about the application of systems engineering approaches. In the final Learning Session, we conducted an exercise in which teams identified opportunities to apply the systems engineering tools they learned to new processes that needed redesigning due to COVID-19. For identified processes, teams outlined the systems engineering approaches they would apply and considered ways in which they could design processes sufficiently robust to address equity concerns.

All project teams fulfilled reporting requirements, including "storyboards" or presentations for each Learning Session and one "EHRLL transformation reflection (ETR)" assignment during the period intervening between Learning Sessions. These reports required teams to clarify their project aims; define and report a set of process, outcome, and balancing measures and data sources that were specific to their project; and report on progress toward design elements and concepts introduced at preceding Learning Sessions and reflect on lessons learned.

Clinicians and engineers from project teams collaborated to evaluate the impact of their projects and to draft papers describing their clinical and engineering work to date. Each team completed a business case analysis to assess potential impact of the implementation of their projects. Teams also prepared and presented abstracts at multiple conferences as milestones toward this end. Each team also published at least one peer-reviewed journal article describing aspects of their projects (see Publications).

The evaluation work combined quantitative assessment of team progress when feasible with meta-analysis via qualitative and survey methods. By observing interdisciplinary learning within and across teams, the evaluation team developed a deeper understanding of how interdisciplinary team learning occurs. This understanding will inform spread efforts as well as future learning collaborative initiatives. We also broadened the scope of our evaluation to include the perceptions of the engineers, who – as embedded R&D team members – could provide feedback about project progress, goal accomplishment, and barriers and effective strategies for applying systems engineering in healthcare. Our qualitative work also emphasized the role of patients on multidisciplinary R&D teams and summative assessments of how learning ecosystems function.

In Years 1, 2, and 3, evaluation team members (part of the Admin team) conducted and analyzed qualitative data for our meta-analysis of learning within and across interdisciplinary teams. Evaluation team members attended each project team's regularly scheduled meetings and took detailed notes to capture salient comments and contextual factors. Notes include commentary about our observations of the meetings and team members' interactions. Evaluation team members drafted memos that identified similarities and differences observed across the teams and ways that ongoing observations confirmed or contradicted the evaluation team's theories around the challenges and strategies related to learning that are apparent within and across teams and met to discuss observations, edit memos, and revise the current research questions. We also conducted one-on-one semi-structured interviews with members of each of the project teams. Interviews lasted approximately 30 to 60 minutes, were audio recorded with participant consent, and asked participants to identify external challenges to his/her team's progress and strategies the team has used to address these challenges. In order to ensure a diverse range of perspectives, interviews were conducted with clinicians, health system staff, engineers, and patient partners from each of the teams. The semi-structured interviews were transcribed, verbatim, by a third party. We also conducted focus groups with each of the project teams. At each focus group, one member of the evaluation team guided the team through a survey that asked participants to rank the challenges the team had faced and predicted they would face in the future (from greatest challenge to weakest challenge to team progress) and to identify strategies the team had used, and could use, to address the greatest challenges. A second member of the evaluation team took notes. The focus groups were recorded and transcribed, verbatim, by a member of the evaluation team. We used field notes and the transcripts from the semi-structured interviews and focus groups to perform our meta-analysis, facilitated by NVivo qualitative software.

In Years 4, 5, and 6, evaluation team efforts centered on collection and analysis of qualitative data for our meta-analysis of learning within and across interdisciplinary teams. We conducted summative evaluation interviews with key informants on each of the three project teams, including clinician, engineering, and project management team members across the three projects (a total of nine interviews). The summative evaluations covered the following areas: (1) overall experience in the learning lab and view of its aims and objectives; (2) barriers experienced throughout the intervention period; (3) overall learnings and assessment of various elements of the learning lab program; (4) future directions of the innovation work and drawing on learnings during the intervention; and (5) the learning lab's successes and shortcomings. We developed an interview guide through multiple rounds of cognitive testing and revision. In each instance, interviews ranged from 30 to 60 minutes and were transcribed by a third party. Two members of the evaluation team coded the interviews in an iterative manner to develop grounded theory and identify emergent themes.

In addition, the evaluation team collected and analyzed qualitative data to study the process of patient engagement in the context of interdisciplinary quality improvement initiatives. Evaluation team members conducted one-on-one, semi-structured interviews with patients and patient representatives on each of the project teams in addition to interviews with other team members (17 interviews total).

Interviews were audio recorded with participant consent and transcribed via a third party. In addition, evaluation team members had “patient engagement lunches,” organized by EHRLL leadership, at which the focus was understanding and promoting patient engagement on each project team. At each meeting, at least one evaluation team member took detailed notes. Field notes and the transcripts from the interviews constituted the data were used to perform an analysis of the contributions made by patients/patient representatives and of the mechanisms by which these contributions occur. We used NVivo software to facilitate data analysis.

Finally, the evaluation team consolidated reporting by R&D teams to track progress in transformation reflection and storyboard assignments. At each Learning Session, the evaluation team also administered evaluations that we used to modify the format and content of the Learning Session. At the same time, we asked participants to complete a structured questionnaire about their team's progress toward accomplishing project goals and their personal learning about systems engineering concepts introduced through EHRLL.

Training and professional development

EHRLL offered three main opportunities for training and professional development: weekly or biweekly team meetings, Learning Sessions, and (approximately) bimonthly reports.

First, at weekly or biweekly team meetings, we convened multidisciplinary R&D teams, including clinicians, non-clinicians, embedded engineers, and Admin Core members with organizational and operational expertise, to work on each team's project. This forum provided an opportunity to exchange expertise across participating disciplines. In particular, we used regular meetings to train clinicians and non-clinicians to use and appreciate specific systems engineering methodologies, including methods for mapping processes, stratifying risks, prioritizing failure modes and effects, and developing robust and reliable design. In turn, engineering, organizational, and operations experts learned about the clinicians' perspectives and about specific clinical content areas on which each project was focused.

Second, Learning Sessions extended the training and professional development of EHRLL participants by offering opportunities for teams to learn from each other about the application of systems engineering tools and about the specific problems that were the focus of each project. Though each team worked on its own project, there were elements of all of the projects that were relevant across all health systems. Project team members were able to compare and contrast methods applied and challenges encountered and addressed across projects, not just within their own. Each Learning Session also provided explicit training about new systems engineering approaches or concepts that projects were asked to apply in subsequent weekly meetings. The role of the ‘disruptor’ was key at several Learning Sessions as disruptors to challenge teams and help them learn. Additionally, in Year 4 and 5, patient safety and quality leaders from the participating teams' own institutions attended most Learning Sessions in the role of ‘disruptors’, as sustaining their work and spreading it within their institutions became increasingly a focus of attention and leadership buy-in and awareness of the work became increasingly important.

Third, at each Learning Session, R&D teams produced storyboards and, in the interim work period, submitted EHRLL Transformation Reflections (ETRs). These reports provided opportunity for teams to reflect on their own progress and learn from consolidating their thinking into materials that can be shared. Feedback on each assignment from Admin and Engine core leaders was also designed to promote learning.

Limitations

EHRLL faced a variety of limitations. COVID-19 adversely impacted progress of all of our R&D teams, as clinician members were called upon to lead efforts in their respective institutions to respond to the pandemic. COVID-19 also stalled progress of the learning lab as a whole, as it caused cancellation of learning activities, including our March 2020 learning session, and forced other activities online. More importantly, however, project progress was impeded by continuity in teams' focus. Exacerbated by personnel turnover, the lack of continuity slowed momentum and impeded progress of specific R&D teams when transitions occurred. Ultimately, the health systems in which our R&D teams were based never really got invested in supporting these projects in a way that they/we needed to prevent discontinuity in the face of competing institutional priorities.

Third, research publications resulting from this grant, which focused on the learning lab as a whole, relied largely on qualitative methods; although these were capable of providing profound insight about the organizational, operational, and contextual factors that enable learning in interdisciplinary ecosystems, the qualitative methods were based on perceptual reporting, which may reflect social desirability bias. We mitigated this by following teams over time and by combining observations, interviews, focus groups, and surveys.

Results (Principal findings, outcomes, discussion, conclusions, significance, implications

In this section, we divided results into project lifecycles, cross-project evaluation, training and professional development, and dissemination.

<u>Project lifecycles</u>

EHRLL resulted in the following:

Aim 1: We built and refined a re-engineering and shared learning infrastructure, including an Administrative/Learning Core, an Engineering Core, and multidisciplinary teams of investigators, engineers, and, to a lesser extent “Disruptors,” from outside healthcare that stimulated a systematic approach for identifying, designing, developing, spreading, and evaluating patient safety innovations. Though R&D teams varied in their approach and progress, all made strides toward accomplishing process redesigns. Efforts to carry forward lessons from EHRLL continue in an ongoing Patient Safety Learning Lab, “Closed Loop Diagnostics” (HS027282), spawned by EHRLL’s leadership team.

Aim 2: EHRLL engaged in four research projects that applied systems engineering and operations management theory and methods to develop innovative, cross-disciplinary team-based solutions for improving HIT-supported processes for high-risk patients, referrals, and tests and designing highly reliable systems with an emphasis on future generalizability. Project 1, which ended early, was replaced by Project 4 in Year 2.

Aim 3: R&D teams implemented elements of redesigned processes in their hospital/community-based primary care practices to varying degrees; their design work explored and sought to ensure the generalizability of their processes in alternative settings and with other medical conditions.

Aim 4: We identified measures for assessing redesigned processes. However, data acquisition for this ongoing measurement varied across teams and measures. Although we may not know the full impact of redesigned processes on practice, team, provider, and patient outcomes, we analyzed information available and used extensive qualitative assessment where quantitative information was lacking.

The project lifecycle for each team differed as follows:

Project 1 identified high-risk patients and implemented its re-engineered urgent referral management system via referral coordinators, primary care, and specialty practices across 15 health system practice locations. They continued to refine the process drawing on lessons learned from their initial implementation attempt. Project 1 ended its participation at the end of Year 3, after redesigning an idealized process. During Year 4, they served as a “spread site” for other project teams by exploring the potential for application within the health system and providing feedback to others about their redesigned processes.

Project 2 used results from its overall analysis to design a new and widely supported preoperative care process that frontloads the work to improve patient experience and reduce adverse events, lengths or stay, and hospital readmissions. This care pathway has formed the basis of an American Academy for Cerebral Palsy and Developmental Medicine spinal fusion care pathway. Based on learnings, the team developed a series of videos to inform patients and families considering spinal fusion surgery, which remain featured on the Courageous Parents’ Network: https://youtu.be/QjGbPMR9WnQ. They are also spreading design elements to progressively more challenging surgeries, including hip, craniofacial, and multiple procedures under single anesthesia.

Project 3’s R&D team designed a more reliable process for testing urine toxicology for all patients receiving chronic opioids into clinical workflows, which resulted initially in a dramatic increase in the number of patients with urine drugs tests (UDTs). They also developed a provider dashboard with interactive usability testing in order to motivate behavior change and help-seeking behavior by physicians.

This innovative dashboard had to be suspended when the organization shifted from a home-grown EMR to a commercial system (Epic). They were unable to re-establish the functionality of the priority opioid population dashboard, given limitations on data availability. They also designed, with input from patients, a new standard process for ensuring naloxone prescribing for patients at high risk of overdose. They have redesigned the prescription refill process for opioid medications, re-engineering prescribing from paper based to electronic opioid prescribing. Team leadership collaborated with their organizational opioid resource team and initiatives in order to coordinate the work of the EHRLL team to maintain alignment with the dynamic hospital-wide goals and policies. The team leveraged patient partner input to revise a hospital-wide opioid treatment agreement to support appropriate opioid prescribing and designed, tested, and commenced implementation of a workflow process for these agreements. They also used patient input to develop a patient survey for patients with chronic pain on opioid medication. Learnings from this survey informed the team's ongoing improvement efforts. Additionally, they designed an idealized data dashboard and have been pursuing access to the data required to achieve its realization. The project coordinated with efforts to aid clinicians in interpreting and acting on urine aberrant toxicology report results. The team empowered practice pharmacist and nursing resources to help screen and better assist patients and their prescribing physicians in a safer and more patient-centered workflow.

Project 4's problem analysis enabled the R&D team to identify five priorities for redesign: (1) communication, (2) standard definitions, (3) medication reconciliation, (4) learning curve for patients/caregivers in the hospital, and (5) the transition home. The team delayed process redesign efforts to achieve stakeholder buy-in, which problem analysis revealed needed to include inpatient hospital leaders and staff members. Team members first completed a scoping review (peer and literature) and used it to validate process "drivers." Then, by sharing findings with key stakeholders, they attained support for initiating driver-related changes. The R&D team collaborated with a larger working group, the High-Risk Working Group, at the health system, in order to integrate the goals of their EHRLL project within the larger health system. Process redesign efforts focused on developing a shared care plan among the inpatient team, primary care providers (PCPs), home care, and the patient. The High-Risk Working Group was disbanded before all aspects of the process redesign were implemented. However, the new project leader was invited to participate in a new, similar working group. Efforts among this group were delayed due to COVID-19.

Please refer to the list of publications at the bottom of this report for additional results stemming from individual projects.

Cross-Project Evaluation

Learning Session evaluations suggest that team members generally liked and appreciated the mix of activities, with preference for hands-on exercises and separate time to brainstorm and plan as a team. Throughout our grant period, we relied on Learning Sessions, which we found more impactful than webinars and conference calls, for bringing all the participating organizations together. We used a half-day format for our Learning Sessions, which were each followed by an Administrative Core team meeting after the Learning Session for follow-up and reinforcement.

Analysis of participant observation, interview, and focus group data enabled us to describe the constraint management process, which demonstrates how R&D teams experience hierarchical and heterarchical constraints at different stages of innovation and address them by applying direct and indirect tactics in order to achieve milestones and maintain momentum.[40] Although both constraints could appear at any time during the innovation process, we observed that hierarchical constraints posed challenges especially in the design/implementation and sustaining stages of innovation, whereas heterarchical constraints posed challenges more often in the design/implementation and scaling stages of innovation. In response, teams invoked various tactics to continue making progress on their innovations. To address heterarchical constraints experienced while designing and implementing innovations, teams used tactics that included reliance on data and making a case to exchange resources. To address hierarchical constraints experienced while scaling innovations, teams used tactics that included workarounds, creating a presence, and signaling support. To address both heterarchical and hierarchical constraints that were equally present when teams sought to sustain innovations, teams used empathic listening and information gathering to overcome them.

Our analysis also showed key elements of a successful learning ecosystem,[41] one in which teams learn to innovate and work around challenges they face. Specifically, we showed that an effective learning system creates alignment, or fit between what the teams do and the context in which they operate, along four primary dimensions: interpersonal/interprofessional, structural, informational, and processual. The interpersonal/interprofessional dimension is supported by creating a safe space, integrating clinician versus engineering views, and gaining stakeholder support. The structural dimension is supported by managing team membership and allocating resources to teams. The processual dimension is supported by engaging in learning activities and carving out learning time. And the informational dimension is supported by selecting appropriate priorities and expanding team member perspectives across disciplines. The learning ecosystem also facilitates a series of team practices that support the alignment throughout the project's life, and our research highlights these practices as they were described by interviewees and represented in our observations of team meetings over the past several years. The learning ecosystem was a unique feature of EHRLL, namely in creating an environment for learning and innovation through a collaborative network; however, such efforts can be conducted more broadly and in other settings, and our findings on the learning ecosystem show what it takes to do so.

Our study of the process of patient engagement showed how the role of patients changes throughout a project's lifecycle—and should change to optimize team progress and adapt to changing conditions pertaining to the team's objectives.[42,43] In particular, building on social identity theory, we describe how patient and team member perceptions of patient engagement evolve and how such perceptions can influence and be influenced by the changing role and contributions of patients on redesign teams. As we explain: Patients can move across the informant, partner, and active change agent spectrum, through shifting views of patients' roles within teams, which shape patients' and team members' behavior. Behaviors subsequently impact the way patients can contribute to the team's work, and these contributions serve as feedback that further modifies the views of the patient's role among patients and team members. Moving through stages of the spectrum hinges on the dynamics between perceptions, behaviors, and contributions and the feedback loop between patient contributions and team members' perceptions of patients. As patient team members add value, their standing within the team changes, leading to a change in the position-based schema both patient and non-patient team members apply to the experience of working together. In revising this schema, team members' views of the patient's role changes, allowing patients to transition from informants to partners to active change agents.[43]

Participant evaluation of the learning lab indicated moderately high marks, ranging from 3.75 to 4.69 on a scale of 1 to 5.[41] This suggests that participants generally agreed that they felt satisfied with their team's progress, the learning lab, their team's learning, and participants' individual learning. Participants scored highest the question indicating that their personal understanding of systems engineering tools had improved. In general, patients offered higher marks than engineers and clinicians (4.60 on average for patients versus 4.20 and 4.21 for clinicians and engineers, respectively).[43] Across all responses, clinicians offered the lowest mean scores for two items: 3.40 (suggesting only somewhat higher than neutral) regarding their satisfaction with team progress and the need for more help with measuring processes and outcomes.

Participant self-evaluation of team progress toward implementation suggested that, on average, participant understandings improved in nine of nine areas measured.[41] The most substantial improvements were in detailing and specifying process designs and patient engagement. In these areas, learning lab participants reported 78.6% and 73.1% improvements, respectively. These data suggest that the learning lab fostered the development and improvement of systems engineering skills. The least improvement was in identifying process and outcome measures and making them available for the project. In this area, learning lab participants reported 35.5% improvement. The three teams have plans to sustain and spread efforts, ranging from handing off a pilot program to a standing committee to launching a permanent, system-wide center.

Training and professional development

All EHRLL participants across all disciplines and ranks engaged in training and professional development. Participants learned across teams and from others with different disciplinary backgrounds (engineering, clinical, organizations, quality improvement) and with different roles and responsibilities (frontline personnel, clinic managers, students, and patients). Individuals derived leadership opportunities through their participation in EHRLL.

At Brigham and Women's Hospitals, four junior faculty physicians assumed leadership of the R&D team in sequence. At Mount Auburn, one junior faculty physician assumed leadership of the R&D team after the retirement of two senior physicians. At Boston Children's Hospital, one junior faculty physician developed markedly in his leadership role, gaining national and international prominence during the course and, in part, through his work with EHRLL. In addition to providing a development opportunity for each of these young physician leaders, trading leadership among physician-team members promoted engagement with systems engineering of talented physicians and enabled continued team momentum.

It is worth noting that learning from and among patients became an important emphasis of EHRLL's learning program. As participating patients increasingly became partners and leading change agents rather than visitors or consultants to their R&D teams, patient suggestions grew more numerous and their authority increased. Interviews by evaluation team members suggest that team members felt they learned from patients such that the impact and outcomes of the team's work were significantly enhanced. We also provided opportunities for patients to learn from and to support each other by convening patients together, separate from other team members, to discuss common challenges and goals for participating within their respective R&D teams.

Additionally, through the learning lab's use of embedded engineers within each participating health system's project team, 25 industrial and systems engineers, were involved in this work and experientially trained about healthcare problems, how to apply systems engineering in meaningful ways, the attendant challenges faced in this work, and strategies to overcome these challenges. The embedded engineers were fully integrated members of each project team, participated in learning sessions with their teams, facilitated applying quality improvement (QI) and engineering methods, and served as general resources and team members.

Dissemination

An explicit goal of the program was to share learning across project teams. We did this in two ways. First, we disseminated results by providing shared learning opportunities at each Learning Session. At the Learning Sessions, we required projects to develop a storyboard describing project aims, intended metrics and preliminary results, and lessons learned. We also devoted a portion of the agenda to allow team members time to review each other's storyboards, to present their results to one another, and to ask questions. Second, we disseminated results through core team members who served on multiple project teams. These team members worked to transfer key insights about what's working in one team to the other teams they supported.

Another key community of interest was other Patient Safety Learning Labs. To this end, EHRLL leaders regularly submitted to the AHRQ PSLL newsletter and participated in the in-person or online meetings of the AHRQ Patient Safety Learning Labs, at which we have served as panelists on behalf of EHRLL, and presented in several AHRQ PSLL webinars. In addition, we invited the PI from the NYU PSLL to present and exchange lessons with our learning lab teams. This experiment was extremely well received.

A third community of interest is the community of scholars and practitioners with shared interests. To address this community, EHRLL leaders and participants organized and hosted the 2019 I-PrACTISE Conference, held June 2-4 2019 in Boston in partnership with the Healthcare Systems Engineering Institute and the University of Wisconsin Department of Family Medicine and Community Health. EHRLL project teams attended, presented posters on their work, and co-led various plenary sessions. An EHRLL faculty member presented the keynote address on diagnostic errors, and other EHRLL faculty members, as well as patient partners from the Boston Children's Hospital and Mount Auburn Hospital teams presented a very successful session on patient engagement. EHRLL co-PI and faculty member James Benneyan, PhD, was named director of I-PrACTISE in 2019.

Our main activity for reaching scholars and practitioners has been through publications and presentations. EHRLL project teams have sought to publish and present their project results at conferences and in peer-reviewed journals (see Publications). In addition to dissemination of project results and qualitative students, several papers,[44,45] abstracts,[46-51] and conference presentations[51-54] were produced, describing the application of systems engineering methods.

Conclusions, significance, implications

Many challenges confronting health systems require novel approaches to enable interdisciplinary teams to innovate and improve the quality of complex organizations and processes at critical junctures of care. Through ERHLL, we created an ecosystem to foster innovation. Although organizational conditions were not always ideal for teams to make progress, four interdisciplinary EHRLL R&D teams engaged in process redesign projects over 5 years to learn how to innovate to achieve improvement goals. Our experience builds on organizational learning theory, suggesting that alignment between a team's organizational context and its innovation project requires continuous learning and adaptation; when there is alignment, innovation teams can continue to learn to innovate and achieve innovation progress. Team member turnover highlighted the importance of having tools to manage team membership over time, such as more formalized onboarding processes. Gaining and maintaining stakeholder support was critical not only for the implementation and spread of redesign efforts but also for boosting team member morale and further promoting a learning experience. Learning ecosystems like EHRLL can serve as a conduit enabling interdisciplinary teams to achieve alignment between the dynamic organizational context and the demands of the team innovation projects. That none of our learning lab teams achieved strong alignment in all four areas, typically missing at least one, highlights the challenge of achieving sufficient alignment to accomplish improvement objectives.

Key considerations for creating an interdisciplinary learning ecosystem can be used as a starting point for new learning labs. Before innovation activities begin, health systems must organize the capacity to ensure they can create and maintain a core leadership team; adequate resources; and team members with interest, knowledge, capacity, and enthusiasm for undertaking the proposed effort. As the work proceeds, teams need capacity to sustain alignment and to manage constraints that might undermine their work. Particularly with natural attrition of team members over time, realignment must occur on an ongoing basis. Throughout the innovation process, teams must make opportunities to reflect in order to internalize their learning, and they must consider plans for spreading and sustaining their innovations.

Lessons from our learning lab suggest that interdisciplinary ecosystems have the potential to foster learning for improvement and innovation. Our learning lab created an environment conducive to interdisciplinary collaboration, innovation, and adoption of systems engineering and design methods. Although study participants described some shortcomings of the learning lab, we showed that a successful learning ecosystem can facilitate alignments as they need to occur for teams solving complex problems and functioning across multiple organizational levels.

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In response to COVID-19, EHRLL's Engineering Core team, developed the Northeastern University Hospital Surge Capacity Planning Model to help health systems estimate and visualize 1- to 30-day ahead hospital-specific demand for key resources, including medical and ICU beds, ventilators, PPE, medications, and available staff on a rolling basis. The tool was made freely available to any health system worldwide. It has been viewed more than 17,000 times in all 50 states and more than 90 other countries, and over 200 health systems registered to receive updated versions.

Information below is from the AHRQ website referenced above:

The COVID pandemic is placing enormous surge demand and strain on health system capacity, staff, personal protective equipment (PPE), and other supplies, individually and regionally. Many hospitals and policymakers need real-time information about these evolving demands to make critical operational decisions.

Northeastern University developed the Hospital Surge Capacity Planning Model to help health systems estimate and visualize 1- to 30-day–ahead hospital-specific demand for medical and ICU beds, ventilators, PPE, medications, and available staff on a rolling basis.

The tool was made freely available to any health system worldwide, by downloading from the COVID models website at https://www.hsye.org/covid-19-capacity-mgmt. The developers rapidly created this model by adapting and integrating 10 years of prior research supported by the Agency for Healthcare Research and Quality, the National Science Foundation, and the National Institutes of Health. The overall objective is to provide early signaling of capacity, supplies, and staffing concerns at hospital and system levels.

This model can complement more macro-level epidemic models informing public health policies, most using conventional susceptible-recovered concepts. The approach blends theoretic and data-driven modeling methods to produce detailed actionable decision support, integrating factors such as current patient census by type and local new COVID case predictions.

The model can be used in a number of ways to help hospitals prepare for and manage capacity concerns from COVID-like epidemics, including providing general information, informing operational decisions, and expediting significant concerns. The model can help answer questions such as:

- How many patients will a hospital have in the ICU each day, and how many are going to be ventilated?
- When should a hospital convert routine space to ICU or isolated beds?
- Given inherent variability (e.g., random lengths of stay), what is the probabilistic range of results a hospital might expect over the next week and month?
- When should a hospital enlist retired caregivers, primary care providers, and others in staffing routine healthcare acute care setting delivery needs?

The model is implemented in Excel for ease of use and sharing. The file consists of five worksheet tabs—one each for bed demand, PPE consumption, staff availability, input instructions, and calculation FAQs. Results are displayed graphically as run charts over time and tabularly, formatted for printing to facilitate bed huddles, surge management meetings, and other clinical team communications.

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