# Opportunities for Innovation to Enhance the Image Ordering Process

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## OBJECTIVES

This thesis presents ongoing work at the Center for Evidence-Based Imaging in efforts to identify opportunities for innovation to enhance the image ordering process leveraging healthcare information technology (IT) tools. We sought to explore these opportunities with the following research objectives (A separate manuscript is being submitted to a peer-reviewed journal for each research objective described below):

**Research Objective 1:**

**To quantify data documented in Emergency Department provider notes at the time of image order entry**

We hypothesize that there is a significant amount of clinical data present in the medical record that, if harvested in a timely fashion, may be used to augment order requisition saving providers from time-consuming entry of redundant data.

**Research Objective 2:**

**To assess rates of clinical decision support (CDS) attributes present in emergency department provider notes at the time of image order entry**

We hypothesize that there is a significant amount of clinical data available in the medical record prior to order entry that may augment the process of completing specific CDS or suppress provider exposure to unnecessary CDS alerts if the specific rule is not applicable prior to the decision to place an order for an imaging study.

## SIGNIFICANCE

With broad proliferation of electronic health records (EHRs), there is general consensus that many opportunities for optimization of health IT tools remain. For example, providers are often required to enter redundant clinical data about the same patient to complete various clinical tasks. In addition to the obvious resulting workflow inefficiencies, providers may enter incomplete or conflicting clinical information that may adversely impact communication among providers and diminish the quality of care for patients. This documentation of incomplete or conflicting clinical information also has significant impacts on the secondary use of clinical data such as for analysis of guideline adherence or clinical research. For instance, providers are required to document patient assessment and plan in the form of a note (often using a template) in the EHR while in a related workflow sequence within minutes are required to enter redundant clinical information in the order entry module of the same EHR to request an imaging study, such as a CT scan or a chest x-ray for the same patient. In another example, providers are routinely exposed to clinical alerts (such as clinical decision support) unnecessarily resulting in alert fatigue, a well-described phenomenon where providers routinely ignore most, if not all alerts. Thus, reducing or minimizing redundant data entry and unnecessary alerts will make EHRs more effective and useful to providers and patients.

The ordering of imaging studies is a common experience across most specialties in medicine. There are multiple points in the image ordering process that represent opportunities for improvement. Interaction with image study order requisition as well as with CDS tools within the computerize physician order entry (CPOE) system are reliant on the ordering provider to enter clinical data such as indications for imaging, signs, symptoms, exam findings and diagnoses to be used to communicate to the radiologist responsible for interpreting the imaging study or to determine the appropriateness of the study in the clinical context. Both research objectives explore clinical notes present prior to image ordering as a source of information that may be used to augment the image order requisition as well as the CDS tool to relieve the clinician from the responsibility to enter unnecessary redundant data taking valuable time away from other aspects of the care of the patient while reducing errors from incomplete or incorrect image order requisition in the EHR.

**Research Objective 1: To quantify data documented in Emergency Department provider notes at time of image order entry**

## BACKGROUND AND SIGNIFICANCE

In addition to its benefits, growth of healthcare information technology (IT) has introduced new quality of care and patient safety challenges. Among eight types of health IT-related sentinel events identified by The Joint Commission between Jan 1, 2010 and June 30, 2013, 24% were due to workflow and communication issues, second only to those attributed to the human-computer interface (33%).[1] Computerized physician order entry (CPOE) has contributed to challenges in communication between members of the healthcare team. In the case of radiology, there is a paucity of clinical information communicated from physicians ordering imaging studies at the point of order entry to radiologists who will subsequently interpret the studies. In a survey of radiologists, 72% reported not receiving enough clinical information about patients, and over 87% reported that more information could lead to a change in study interpretation.[2] This communication gap can have significant negative impacts on patient care and interpretation quality.[3,4]

The pressures of time and resource constraints in the Emergency Department (ED) environment magnify the challenges of workflow and communication. Priority is given to entering orders in a timely fashion; documenting the encounter is a secondary priority. The use of imaging in the ED has increased over time, and by 2010, nearly half of all ED visits included at least one imaging test.[5]

Accounting for approximately 2% of all ED visits,[6] the complaint of headache is also one of the most common for which head CT is obtained in the ED. The national *Choosing Wisely®* campaign has identified head CT in patients with headaches as one of its targets for reduction of potentially wasteful or unnecessary medical tests.[7]

## OBJECTIVE

We sought to evaluate the data documented in electronic health record (EHR) notes prior to CT image ordering for ED patients presenting with headache. We hypothesized that a significant amount of clinical data is present in the EHR notes that, if extracted in a timely fashion, could be used to augment or prepopulate indications provided in the image order requisition, saving providers from time-consuming entry of redundant data and improving communication between ordering providers and interpreting radiologists.

## MATERIALS AND METHODS

### Setting and population

The requirement to obtain informed consent was waived by the IRB for this Health Insurance Portability and Accountability Act-compliant, observational retrospective study of patients who visited the ED of a 793-bed, quaternary care, Level 1 trauma center, academic hospital with 61,000 annual visits. We evaluated all encounters for adult patients who presented to the ED during the 18-month period 4/1/2013 – 9/30/2014 with a chief complaint of headache who had a head CT performed.

### Data collection

In the ED documentation clinical data warehouse, providers separately documented sections of notes such as chief complaint, history of present illness (HPI), review of systems, past medical history, physical exam, initial assessment and plan (A/P), updates to the ED course, and attending notes. A timestamp was attached to each revision of each note portion when it was submitted and when the fully completed note portion was signed. We extracted note sections of interest and submission timestamps from 85,916 ED encounters for 55,179 unique patients during the study period including chief complaint, HPI, initial A/P, and attending notes. As the ED Discharge Data Tool used to extract note section and timestamp data output the timestamp of the first submission of each note along with the complete and signed text string for each note portion, we identified the time stamp of note section completion and signing by reviewing notes from patients' longitudinal medical record. Additionally, the ED Discharge Data Tool did not provide the author of the specific note sections.

We then isolated encounters for patients who presented with a chief complaint of headache during the study period, and received a head CT. We extracted the timestamps of the imaging study orders and study order details including indications from the order requisition by querying the institution's radiology computerized physician order entry (CPOE) system (Percipio; Medicalis, Kitchener, Ontario, Canada) and radiology information system (IDXrad; GE Healthcare, Burlington, VT) data warehouse. In the case of multiple head CTs during an ED visit, we used the first CT for our analysis. Data transformation and comparisons of the timing of orders with the timing of documentation were performed using Microsoft Access 2007 (Microsoft, Redmond, WA) and R version 3.2.2 software (R Project for Statistical Computing, Vienna, Austria).

An open source natural language processing (NLP) tool, Apache cTAKES™ (clinical Text Analysis and Knowledge Extraction System) version 3.01,[8] which includes YTEX,[9,10] was used to mine the note sections for Concept Unique Identifiers (CUIs) including a polarity for each concept, where "1" indicates a positive concept and "-1" indicates a negated concept. For example, in the sentence "the patient has nausea, but no vomiting," nausea is a positive concept ("1"), vomiting is a negated concept ("-1"). cTAKES was customized with ontologies of clinical terms from the latest releases of the SNOMED-CT vocabulary files using the NCI-supported Knowledge Representation languages resource description framework (RDF) and process definitions from MetamorphoSys' sub-setting utility [11] and of radiology terms from RadLex.[12] Custom components were developed to allow cTAKES to take its input (JdbcCollectionReader) from a structured data source (a table in MS SQL server), and also write its output (CasConsumer) to the YTEX defined schema. The extraction of the CUIs from the YTEX schema was done using a SQL query with multiple joins for the unique batch name of the job, resulting in a table in which each line contained the CUI and the ID of the source text.

The cTAKES implementation was customized to have its working look-up ontologies and dictionaries in a local MS SQL database, to minimize computing and network overhead and to optimize processing speed. The overall platform was run on a 32-CPU Windows Advanced Server platform with 64Gb of memory. The NLP processing was run in multi-engine mode, with 10 working and one input-output threads configured.

Demographic and clinical data including timing of ED admission and discharge were collected from the institution's clinical data warehouse, Research Patient Data Registry (RPDR).

**Concepts relevant to headache**

We created a list of concepts *a priori* based on literature and expert opinion that are relevant in determining those that are at increased risk of intracranial pathology among patients presenting with headaches to the ED.[7,13–22] We queried the results of the NLP extraction against this list of concepts. The CUIs and concepts terms are provided in Appendix 1.

A neurologist and an internal medicine attending physician reviewed the literature regarding headaches in the ED,[13] and evaluated the extracted concepts and the indications from the order reconciliation present for each encounter where the HPI was signed prior to image order entry. For each set of concepts or indications, the physicians graded whether a CT was appropriate. Any differences were reconciled through discussion until consensus was achieved.

**Outcome measures and statistical analyses**

The primary outcome was the number of clinically relevant concepts (CUIs) relating to headache extracted from the HPI compared to the number of concepts obtained from the imaging order requisition. Secondary outcome measures include rates of note sections that were submitted and signed prior to the time of image study order entry, the total number of positive and negative concepts extracted from the HPI, and comparisons of total and headache-relevant concepts extracted from HPIs signed before and after image ordering.

Analyses comparing the timing of orders with the timing of documentation were performed using Microsoft Excel 2007 (Microsoft, Redmond, WA), and JMP Pro v.10 (SAS Institute, Cary, NC). As the distributions of indications in the image order requisition and extracted CUIs were non-parametric, we used a Wilcoxon signed rank test for comparison of samples. A two-tailed p-value $< 0.05$ was considered to be statistically significant. We created word clouds (wordle.net) and frequency tables of the extracted CUIs and the requisition indications to depict the concepts found in each source.

## RESULTS

### Study population

We identified 2787 consecutive encounters for 2490 patients who presented with a chief complaint of headache during the 18-month study period. A head CT was performed in 666 (23.9%) of these encounters for 626 (25.1%) unique patients (Figure 1). 63.4% of these patients were female and the average age was 51.5 years (range: 18-96, +/- standard deviation 18.2).

### Note section entry and completion

Rates of note section entry and completion prior to head CT ordering are provided in Table 1. Of patients who had a head CT, there was initial submission of an HPI, initial assessment and plan, or an attending note prior to image study ordering in 39.2% (261/666) of encounters. One of these note sections were completed and signed in 24.6% (164/666) of encounters. A fully completed and signed HPI was present in 23.1% (154/666) of encounters.

**Concepts relevant to headache**

In the subset of 154 encounters with a fully completed and signed HPI, the number of NLP-extracted CUIs specific to headache per HPI was significantly greater than the number of indications per encounter identified in the image order requisition (median 3 vs. 1; p<0.0001) (Figure 2). An average of 28.3 total CUIs were extracted from HPI notes; an average of 3.1 of these were relevant to headaches. There was no significant difference in either the total number of NLP-extracted CUIs or those CUIs relevant to headache per encounter in HPI notes completed and signed prior to image ordering compared to those completed and signed after image ordering (total: median 29 vs. 28 [p=0.29]; relevant to headache: median 3 vs. 3 [p=0.07]) as displayed in Figures 3 and 4, respectively.

**Differences in concepts between sources**

In 143/154 (92.9%) of encounters with a completed and signed HPI prior to image ordering, the extracted CUIs provided new concepts not present in the imaging requisition indications, with an average of 3.03 new concepts (1.03 positive and 2.01 negated) per encounter. In 27/154 (17.5%) encounters, there was at least one concept extracted from the HPI that was also present in the requisition indications, and in 14/154 (9.1%) encounters, there were conflicting concepts either within the extracted CUIs or between the extracted CUIs and the requisition indications. The differences in concepts found between the CUIs extracted from HPI notes and the requisition indications are depicted in Figures 5 and 6, respectively. Concepts extracted from HPIs have an additional dimension as they may be positive (blue) or negated (red) while the requisition indications are limited to only concepts that are present. However, there is a concept for “normal neurologic exam” from the requisition that is a proxy for negated findings.

To evaluate the clinical significance of these findings, we used the consensus grading developed by the two physician reviewers to consider all concepts or all indications present in the encounter to determine whether a head CT was appropriate. In 84/154 (54.5%) of encounters, the head CT was graded as appropriate based on CUIs compared to 87/154 (56.5%) encounters where the head CT was graded as appropriate based on the imaging requisition indications. In 35/154 (22.7%) encounters, the CUIs extracted from notes added value where the indications alone were not enough to grade the head CT as appropriate but the extracted CUIs showed that a head CT was appropriate. For example, an order requisition for imaging had one indication, “acute.” However, extracted concepts from the HPI revealed that the patient had an infectious disease disorder, associated neck pain, numbness, and vomiting. As an example of a case where the requisition was sufficient to show that a head CT was appropriate but the extracted concepts added useful new information, an imaging requisition listed indications of “head trauma, loss of consciousness, and acute.” There was only one relevant extracted concept, “Warfarin Sodium (+1)” which would have been very helpful for the radiologist to know.

## DISCUSSION

In this study, we identified provider EHR documentation that could provide valuable information with the potential to improve communication with interpreting radiologists when ordering an imaging study. Unique, relevant clinical information was present in unstructured provider notes that were either in a submitted or final state at the time of image ordering that, if harvested in real-time, could be used to augment the communication from the ordering provider to the radiologist at the time of this critical patient handoff.

Our findings support previous research that image order requisitions provide inadequate communication from the ordering provider to the radiologist.[2] Even for institutions where the radiologists have access to the EHR, the largest limitation to obtaining more data such as in the EHR is the amount of time required.[2] Although previous work has used NLP in real-time clinical scenarios such as using radiology reports as part of a pneumonia screening tool,[23] our study identifies a novel approach of using NLP to identify discrete data in clinical notes present at the time of the decision to order an imaging study.

We found no difference in the total or headache-specific concepts in HPIs signed before vs. after image ordering. However, HPIs signed prior to image ordering contained significantly more relevant concepts than what was provided in the image order requisition. In 23% of cases where the CT was not found to be appropriate based on the requisition indications, the concepts in the HPI justified the appropriateness of the CT, and in 93% of the cases, the HPI provided new relevant information beyond what was provided in the requisition.

These data must be interpreted in the context of the study design. Our study was conducted in a single academic setting making its generalizability unclear. Physician practice variability is likely high regarding the timing of documentation of notes, also affecting generalizability. Clinical documentation is likely clustered based on individual clinician practice, but due to the inability of the ED Discharge Data Tool to link the author with the note portion, and considering that there are a relatively small number of providers and multiple providers edit individual notes, we did not include clustering in our analysis.

Factors such as context-specific physician workflow, patient needs, and access to workstations limit the amount of data documented in the EHR by the time of image order entry, particularly in the ED. Although clinicians likely prefer to perform documentation as near to the encounter as possible, that goal is not often possible due to the constraints. However, given the significant amount of useful data we found present at the time of imaging order entry gives encouragement that favorable rates could be found at other institutions. Additionally, as means of documentation become more mobile and closer to the point of care, the more likely we expect that useful data will be available prior to image ordering. Our study only looked at encounters for patients with chief complaint of headache making the generalizability unclear applied to other complaints. However, rates of HPIs with data submitted prior to image order entry were similar for the total number of (non-headache) encounters during the study period (Table 2), as well as the five most frequently occurring chief complaints for patients for whom head CTs had been obtained.

Clinical documentation, whether complete and signed or not, is imperfect by its nature when compared to the true state of patient health, falling short of capturing all pertinent positives and negatives relevant to the chief complaint. These imperfect data will not be able to completely replace order requisitions or clinical decision support (CDS), but we have demonstrated that there is a significant amount of useful and unique information available at the point of order entry to effectively augment order requisitions to improve the communication between the ordering physician and the radiologist without additional burden to the ordering physician.

Celi et al describe a future state optimal data system[24] where EHR data including clinician documentation are fully integrated and provide real-time “bidirectional data streams” to inform downstream processes such as image ordering or CDS. Demner-Fushman et al describe applications in which NLP can drive CDS when integrated with the EHR.[25] This study takes a step toward that goal by recognizing that there is valuable underutilized information in the living document of a clinical encounter.

Future work will be needed to evaluate if these data can inform CDS. In addition, further work is needed to integrate and automate the extraction of these data to populate order requisition to enhance the ordering process. These efforts, if successful would free the ordering physician from the need to enter redundant data likely already present in the EHR. As the socio-technical environment progresses and the ability to document clinical notes gets closer to the bedside, we expect more data will be available that can further be used to inform and drive downstream processes in patient care, enhancing the meaningful use and efficiency of the EHR.

**CONCLUSION**

Clinician documentation in the EHR provides a resource of valuable information that is present in a significant percentage of encounters at the point of image ordering that, if leveraged in a timely and automated fashion, could improve the communication between the members of the healthcare team when ordering an imaging study to help improve quality of care and improve efficiency.

**Research Objective 2: To assess rates of clinical decision support attributes present in emergency department provider notes at the time of image order entry**

## BACKGROUND AND SIGNIFICANCE

Clinical Decision Support (CDS) is an effective integration of health information technology (IT) to deliver timely education at the bedside. A significant challenge with CDS is leading physicians to cancel orders they are already in the process of ordering.[26] One of the ten commandments of imaging CDS is to "respect the ordering provider workflow," particularly with respect to eliminating redundant data entry.[27] In our current CDS model within the computerized physician order entry (CPOE), physicians enter patient data for CDS at the time of order entry leading to significant interruption of workflow as well as redundancy of documentation.

The Emergency Department (ED) is an environment that benefits from the implementation of CDS where healthcare providers are expected to make clinical decisions rapidly and do not have a significant amount of time to research a topic to determine the evidence supporting the use of a diagnostic procedure given a clinical scenario. CDS has been shown to be an effective means to improve practices in the ED. Imaging-specific CDS based on high quality evidence resulted in 20% reduction in utilization and 69% increase in yield of CT pulmonary angiography for the evaluation of pulmonary embolism in ED.[28]

The National Emergency X-Radiography Utilization Study (NEXUS)[29,30] and the Canadian C-Spine (CCS) Rule[31] are well-validated CDS instruments to clinically rule out cervical spine injury to reduce unnecessary cervical spine imaging that have been implemented at our institution for CT and plain film images of the cervical spine when trauma is indicated on the order requisition (NEXUS) and 6 view plain films of the cervical spine when trauma is indicated on the order requisition (CCS).

Although there is not an expectation to document notes prior to placing orders, we previously showed that there was a significant amount of unique, relevant clinical information present in unstructured provider notes that were either in a submitted or final state at the time of image ordering that could be used to augment the order requisition. It remains unclear whether information from these notes could enhance the CDS process by either identifying CDS rule attributes to augment data entry or identifying exclusion criteria to suppress non-applicable CDS.

## OBJECTIVE

We sought to evaluate the data documented in electronic health record (EHR) notes prior to cervical spine CT or plain film image ordering for ED patients presenting with a history of falls, trauma, or bicycle accidents. We hypothesized that a significant amount of clinical data is present in the EHR notes that, if extracted in a timely fashion, could be used to augment or prepopulate CDS attributes, saving providers from time-consuming entry of redundant data or suppressing CDS when exclusion criteria are met saving the clinician from visual or workflow interruptions and reducing alert fatigue.

## MATERIALS AND METHODS

### Setting and population

The requirement to obtain informed consent was waived by the IRB for this Health Insurance Portability and Accountability Act-compliant, observational retrospective study of patients who visited the ED of a 793-bed, quaternary care, Level 1 trauma center, academic hospital with 61,000 annual visits. We evaluated all encounters for adult patients who presented to the ED during the 18-month period 4/1/2013 – 9/30/2014 with a chief complaint consistent with falls, trauma, or bicycle accidents who had a CT or plain film of the cervical spine performed.

**Data collection**

In the ED documentation clinical data warehouse, providers separately documented sections of notes such as chief complaint, history of present illness (HPI), review of systems, mechanism of injury (including fall height, landing surface, whether motor vehicle rollover or ejection occurred), physical exam, neurologic exam, initial assessment and plan (A/P), updates to the ED course, and attending notes. A timestamp was attached to each revision of each note portion when it was submitted and when the fully completed note portion was signed. We extracted all revisions of note sections of interest, authors, and submission timestamps from 3757 ED consecutive encounters for 3582 unique patients with a chief complaint of falls, trauma, or bicycle accident during the study period. The note sections of interest included chief complaint, HPI, mechanism of injury including whether the injury was due to bicycle accident, motor vehicle accident with rollover or ejection from vehicle, fall height and landing surface, neurological level of consciousness, review of systems, physical exam for head and neck as well as neurological exam, initial A/P, and attending notes. We identified and used the most recent note submission prior to image order entry for our analysis.

We excluded patients identified by Emergency Medicine as activating the trauma team as these patients would immediately be brought for trauma series imaging studies and then isolated encounters for patients who received a cervical spine CT or plain film imaging. We extracted the timestamps of the imaging study orders and study order details including indications from the order requisition as well as associated CDS rule firing and user input attributes by querying the institution's radiology computerized physician order entry (CPOE) system (Percipio; Medicalis, Kitchener, Ontario, Canada) and radiology information system (IDXrad; GE Healthcare, Burlington, VT) data warehouse. In the case of multiple cervical spine imaging during an ED visit, we used the first imaging study for our analysis. Data transformation and comparisons of the timing of orders with the timing of documentation were performed using

Microsoft Access 2007 (Microsoft, Redmond, WA) and R version 3.2.2 software (R Project for Statistical Computing, Vienna, Austria).

Demographic and clinical data including timing of ED admission and discharge were collected from the institution's clinical data warehouse, Research Patient Data Registry (RPDR).

**Decision Support Rule Attributes**

The NEXUS CDS rule identifies a set of five clinical criteria where the absence of all criteria indicates that the patient has a very low probability of cervical injury. This CDS rule was validated based on 34,069 patients at 21 EDs and found to have 99.0% sensitivity for any radiographically evident cervical injury and 99.6% sensitivity for clinically significant injury. Clinical criteria are as follows: (1) posterior midline cervical spine tenderness, (2) evidence of intoxication, (3) alteration in level of alertness, (4) focal neurologic deficit, and (5) presence of a painful, distracting injury.[30] The only exclusion criteria identified in the validation of NEXUS was penetrating neck injury[30] although other exclusion criteria have been used in practice including (1) age less than two years old (caution advised with age less than eight), (2) high risk trauma, as defined by the CCS,[31] and (3) direct trauma to the neck. The CCS exclusion criteria includes (1) Glasgow Coma Scale (GCS)<15, (2) abnormal vital signs, (3) injury greater than 48 hours prior to presentation, (4) age<16, (5) penetrating neck trauma, (6) acute paralysis, (7) known vertebral disease, (8) previous evaluation for the same injury, and (9) current pregnancy.[31]

A neurologist and an internal medicine attending physician reviewed the most recent version of the note portion prior to image order entry and documented attributes of NEXUS and CCS rules including exclusion criteria for encounters where the CDS rule was delivered (56 encounters). Any differences were reconciled through discussion until consensus was achieved.

### Outcome measures and statistical analyses

The primary outcome was the rate of CDS rule attributes identified in the clinical notes available at the time of image order entry compared to the rate of CDS rule attributes obtained via physician interaction with the CDS rule through the CPOE system. Secondary outcome measures included rates of CDS rule delivery in our patient cohort, rates of exclusion criteria from the CDS rules identified in note portion revisions available at the time of image order entry, concordance and kappa statistic of agreement when present both in the CDS tool as well as note portions submitted prior to order entry. Analyses comparing the timing of orders with the timing of documentation as well as concordance calculations were performed using Microsoft Excel 2007 (Microsoft, Redmond, WA).

## RESULTS

### Study population

We identified 3155 consecutive encounters for 2992 unique patients who presented with a chief complaint of fall, trauma, or bicycle accident where the trauma team was not activated during the 18-month study period. Cervical spine imaging (CT or plain film) was performed in 438/3115 (13.9%) of these encounters for 427/2992 (14.3%) unique patients (Figure 7). 55.7% of these patients were female and the average age was 66.9 years (range: 20-105, +/- standard deviation 20.9).

### Note section entry and completion

Rates of note section entry and completion prior to cervical spine image ordering are provided in Table 3. Of patients who had cervical spine imaging, there was a submission of any note portion of interest prior to image study ordering in 42.0% (184/438) of encounters. Of note, there was a submission of an HPI, initial Assessment and Plan, and Attending note prior to image study ordering in 34.7% (152/438), 11.0% (48/438), and 8% (35/438), respectively.

**Rates of CDS Attributes**

NEXUS CDS was delivered in 26.7%(117/438) of the encounters with chief complaint of fall, trauma, or bicycle accident, where imaging was performed of the cervical spine while there were no encounters where CCS CDS rule was delivered. It should be noted that the CCS CDS rule is implemented in the CPOE system to be delivered only when a standard 6 view cervical spine plain film study is ordered with an indication of trauma. 47.9% (56/117) of these encounters had note portions submitted prior to image ordering. 58.1% (29/56) of the encounters with both NEXUS CDS delivered and note portions present prior to image order entry had at least one positive NEXUS criterion (mean=0.64/encounter; range=0-2) and 39.3% (22/56) had at least one negative NEXUS criterion (mean=0.77; range 0-4) identified from the notes. 67.9% (38/56) had at least one mention of NEXUS criteria in the available notes (Table 4).

**Rates of CDS Exclusion Criteria**

There were 3/56 encounters (5.4%) with both NEXUS CDS delivered and note portions present prior to image order entry that had an exclusion criteria indicated in the note submission. For these same 56 encounters, 37.5% (21/56) indicated in the note submission at least one exclusion criterion for CCS rule. 55.4% (31/56) indicated in the note submission at least one absence of an exclusion criterion.

**Concordance of NEXUS Attributes**

Table 5 details the concordance of NEXUS CDS attributes present in the notes compared with those indicated in the CDS tool when each attribute was present in both sources. The overall concordance of NEXUS CDS attributes when present in both sources was 68.4% ($\kappa$=0.35 showing fair agreement).

**DISCUSSION**

In this descriptive study, we made multiple significant observations about information found in unstructured clinical notes present at the time of order entry allowing us to assess data entered in CDS tools more critically. As in our previous study, we identified a significant number of encounters where provider EHR documentation was present and available at the time of image ordering, even in cases involving trauma, falls, and bicycle accidents where one would expect limited amounts of documentation prior to image ordering. We showed this source of information may be applied to CDS rules and exclusion criteria to these rules and that there is a surprising lack of agreement between CDS attributes documented in notes compared to those entered in CDS.

In a previous analysis of the effect of CDS on documented guideline adherence for head CT in the ED for mild traumatic brain injury (MTBI),[32] cases of MTBI were isolated based on whether the CDS for MTBI was delivered when ordering a head CT. However, our findings show that relying on the CDS significantly underestimates the cohort of patients that would be eligible for the CDS likely due to ordering practices. It was previously thought that data collected via a CDS tool represents complete data, although our findings bring this into question. The accuracy of data collected both by CDS tools as well as in clinician notes is also brought into question due to the high rates of discordance for CDS attributes. This study further supports our previous study identifying clinical notes as a valuable source of unique, relevant information that is currently underutilized that may enhance the order entry process. This study was unique in that we were able to extract all versions of note portions of interest and use the most recent note portion submitted, although often incomplete, prior to image order entry

We demonstrated that the information in unstructured clinical notes is relevant and may be applied to the CDS rule in the majority of encounters thus introducing the opportunity to harvest these sources of information in an automated fashion to augment data entry into CDS tools freeing clinicians from unnecessary redundant data entry. CDS Alerts with low specificity lead to high rates in physician override and alert fatigue and efforts are being made to reduce alert fatigue as an EHR-specific patient safety goal.[33,34] We identified exclusion criteria for CDS rules in these unstructured notes, predictably more often for rules limited by a larger number of exclusion criteria. Harvesting these exclusion criteria from the EHR notes may allow suppression of CDS rules not applicable to the current patient, which would free clinicians from unnecessary visual and workflow interruptions, thus reducing alert fatigue. We identified that use of delivery of a CDS tool is insufficient to define a population of patients eligible for the rule based on the small percentage of patients where the CDS rule was delivered. Finally, we found that there is only fair agreement between CDS attributes entered in the CPOE CDS tool and attributes found in notes prior to order entry, raising the question of the quality, sufficiency, and completeness of data entered into either source.

These data must be interpreted in the context of the study design. Our study was conducted in a single academic setting making its generalizability unclear. Clinical documentation is likely clustered based on individual clinician practice, which is likely highly variable, and further work will need to be performed looking at the physician variability in documentation practices as well as data entry into CDS. Identification alone of opportunities to enhance the order entry process using health IT by harvesting these notes may influence future changes in documentation practices if clinicians appreciate an opportunity to save time with downstream processes by investing a relatively small amount of time up front for documentation. Our study only looked at encounters for patients with chief complaint of falls, trauma, and bicycle accidents who received cervical spine imaging making the generalizability to other complaints unclear, but this builds on the work of the previous study on patients with chief complaints of headache expanding the generalizability while also identifying other note portion sources of useful information.

Unlike the previous study, we were limited in taking steps to automate the extraction of the CDS attributes and exclusion criteria from the note portions available at the time of order entry, showing that future work will need to be done in the area of text mining or application of NLP in order to realize a feasible application integrated in the EHR.

This study illustrates that data entered in the EHR and via CDS fall short in multiple dimensions of data quality including completeness, correctness, and concordance.[35] Future work is needed to identify methods of improving the quality of data in the EHR and CDS tools as well as performing validity checks at the point of data entry or data capture. This reinforces a potential future state of a semi-automated process of concepts and attributes extracted from the notes being verified by the clinician when interacting with order entry or CDS tools.

It would arguably be more effective if the CDS tools were integrated more closely with the EHR and could trigger alerts in cases that would benefit from physician action,[25] or alternatively suppress CDS that is identified as not being applicable to the current patient.

## CONCLUSION

Clinician documentation in the EHR is an underutilized resource of information that contains CDS attributes and exclusion criteria and is available in a significant percentage of encounters at the point of image ordering. There is a lack of delivery of the CDS rule evaluated as well as a lack of agreement of CDS rule attributes from the data in the clinical notes with attributes entered via the CDS tool in the same encounter.

**THESIS CONCLUSIONS**

We have shown that health IT tools such as natural language processing may allow real-time extraction of clinical concepts from provider documentation in one part of the EHR to augment the efficiency and accuracy of a related downstream task to improve communication among providers and to help anticipate the need for CDS and to suppress unnecessary alerts. Our work may thus help shift the paradigm of dependence on clinicians to enter redundant data for patients in the process of ordering imaging studies and interacting unnecessarily with CDS alerts. Such an approach can extend beyond these scenarios to apply to multiple workflows to achieve an environment of health care providers interacting with a fully functionally integrated EHR.[24] Recognizing that sources of useful data are being underutilized leading to unnecessary and redundant data entry does not mean that dependence on these data are the end goal, but to use these data to their greatest potential. These works identify a step that we can feasibly take to introduce CDS and other aspects of the order entry process earlier in the encounter. Future work will need to identify opportunities to take further steps earlier in encounters, such as with patient facing applications, to capture data and improve the quality of data captured.

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**TABLES**

Table 1: Summary of note portions that were submitted and signed prior to the time of image order entry

| | | **Submitted Prior to CT Head Order N (%)** | **Signed Prior to CT Head Order N (%)** | | |
|---|---|---|---|---|---|
| CC = Headache | | 666 | | | |
| | ED Chief Complaint | 458 (68.8%) | | | |
| | ED History of Present Illness (HPI) | 226 (33.9%) | 154 (23.1%) | | |
| | ED Initial Assessment and Plan (A/P) | 70 (10.5%) | 46 (6.9%) | | |
| | ED Attending Note | 38 (5.7%) | 0 (0%) | | |
| | ED HPI or A/P or Attending Note | 261 (39.2%) | 164 (24.6%) | | |

CC=chief complaint; ED=Emergency Room

Table 2: Number and percentage of history of present illness (HPI) note portions with documentation initially submitted prior to image order entry for most frequent chief complaints (CC) in patients for whom head CTs were ordered

| | | **Submitted prior to order entry** N | **Total** N | **Percent** |
|---|---|---|---|---|
| **HPI** | Total | 1693 | 6084 | 27.8% |
| | CC = Fall | 183 | 888 | 20.6% |
| | CC = Headache | 226 | 666 | 33.9% |
| | CC = Seizure | 75 | 275 | 27.3% |
| | CC = Dizzy | 95 | 265 | 35.8% |
| | CC = Syncope | 65 | 216 | 30.1% |

Table 3: Summary of note portions that were submitted and signed prior to the time of image order entry

| | | **Entry Submitted Prior to CT Order N (%)** | **Signed Prior to CT Order N (%)** | | |
|---|---|---|---|---|---|
| CC = Fall / Trauma / Bicycle accident | | 438 | | | |
| | History of Present Illness (HPI) | 152 (34.7%) | 44 (10.05%) | | |
| | Neurological Review of Systems (positive or negative) | 16 (3.7%) | 16 (3.7%) | | |
| | Neurological Review of Systems Comment | 6 (1.4%) | 6 (1.4%) | | |
| | Level of Consciousness | 49 (11.2%) | 49 (11.2%) | | |
| | Head and Neck Exam, normal values | 36 (8.2%) | 32 (7.3%) | | |
| | Neurological Exam, normal values | 32 (7.3%) | 32 (7.3%) | | |
| | HEENT Exam Comments | 22 (5.0%) | 18 (4.1%) | | |
| | Neurological Exam Comments | 12 (2.7%) | 11 (2.5%) | | |
| | Initial A/P | 48 (11.0%) | 16 (3.7%) | | |
| | Attending Note | 35 (8.0%) | 2 (0.5%) | | |
| | Any Note Portion | 184 (42%) | | | |

CC=chief complaint; ED=Emergency Room; HEENT=Head, Eyes, Ears, Nose, and Throat; A/P=Assessment and Plan

Table 4: Number and percentage of encounters where NEXUS CDS was delivered where notes submissions present at the time of image order entry contain at least one NEXUS CDS attribute

| | | Encounters (%) | Mean/ Encounter | Range |
|---|---|---|---|---|
| **NEXUS CDS** | Positive Attribute | 29 (51.8%) | 0.64 | 0-2 |
| | Negative Attribute | 22 (39.3%) | 0.77 | 0-4 |
| | Any Attribute | 38 (67.9%) | 1.41 | 0-5 |
| | Total Encounters | 56 (100%) | | |

NEXUS=National Emergency X-Radiography Utilization Study; CDS=Clinical Decision Support

Table 5: Concordance of NEXUS CDS Attributes with Attributes found in note portions submitted prior to image study ordering

| **Midline Tenderness** | | Note submission | |
|---|---|---|---|
| | | Positive | Negative |
| CDS | Positive | 4 | 5 |
| | Negative | 1 | 10 |
| Concordance = 0.70 | | κ=0.37 | |

| **Focal Neuro Deficit** | | Note Submission | |
|---|---|---|---|
| | | Positive | Negative |
| CDS | Positive | 2 | 0 |
| | Negative | 4 | 14 |
| Concordance = 0.80 | | κ=0.41 | |

| **Altered Awareness** | | Note Submission | |
|---|---|---|---|
| | | Positive | Negative |
| CDS | Positive | 7 | 3 |
| | Negative | 3 | 6 |
| Concordance = 0.68 | | κ=0.37 | |

| **Intoxication** | | Note Submission | |
|---|---|---|---|
| | | Positive | Negative |
| CDS | Positive | 2 | 0 |
| | Negative | 2 | 2 |
| Concordance = 0.67 | | κ=0.40 | |

| **Distracting Injury** | | Note Submission | |
|---|---|---|---|
| | | Positive | Negative |
| CDS | Positive | 5 | 1 |
| | Negative | 6 | 2 |
| Concordance = 0.50 | | κ=0.08 | |

| **All Attributes** | | Note Submission | |
|---|---|---|---|
| | | Positive | Negative |
| CDS | Positive | 20 | 9 |
| | Negative | 16 | 34 |
| Concordance = 0.68 | | κ=0.35 | |

CDS=Clinical Decision Support; Neuro=Neurological

**SUPPLEMENTAL TABLES**

Supplemental Table 1: Count of Concept Unique Identifiers (CUIs) extracted from History of Present Illnesses

| Positive CUIs | Count | Negated CUIs | Count |
|---|---|---|---|
| Migraine | 26 | Fever | 73 |
| Vomiting | 26 | Weakness | 53 |
| Weakness | 15 | Vomiting | 34 |
| Neck pain | 15 | Numbness | 33 |
| Shunt | 13 | Neck pain | 29 |
| Fever | 12 | Trauma | 29 |
| Numbness | 12 | Paresthesia | 13 |
| Neck stiffness | 6 | Neck stiffness | 11 |
| Infectious disease | 5 | Head trauma | 8 |
| Malignancy | 5 | Double vision | 6 |
| Subdural hematoma | 5 | Vertigo | 5 |
| Seizures | 5 | Seizures | 4 |
| Cancer | 4 | Migraine | 3 |
| Subarachnoid hemorrhage | 4 | Neurological deficit | 3 |
| Vertigo | 4 | Amnesia | 2 |
| Warfarin | 4 | Instability of gait | 2 |
| Paresthesia | 3 | Thunderclap headache | 2 |
| Head trauma | 3 | Anticoagulant | 1 |
| Aspirin | 2 | Enoxaparin Sodium | 1 |
| Chiari malformation | 2 | Multiple Sclerosis | 1 |
| Congenital AV malformation | 2 | Infectious disease | 1 |

| **Positive CUIs** | **Count** | **Negated CUIs** | **Count** |
|---|---|---|---|
| Double vision | 2 | Meningismus | 1 |
| Lymphoma | 2 | Subarachnoid hemorrhage | 1 |
| Trauma | 2 | Shunt | 1 |
| Vascular dissection | 2 | | |
| Alcohol intoxication | 1 | | |
| Anemia | 1 | | |
| Brain tumor | 1 | | |
| Craniectomy | 1 | | |
| Craniotomy | 1 | | |
| Enoxaparin Sodium | 1 | | |
| Multiple Sclerosis | 1 | | |
| History of aneurysm | 1 | | |
| Multiple Myeloma | 1 | | |
| Obstructive hydrocephalus | 1 | | |
| Plavix | 1 | | |
| Sinusitis | 1 | | |
| Unilateral paresis | 1 | | |

AV - Arteriovenous

Supplemental Table 2: Count of imaging requisition indications

| Indication | Count |
|---|---|
| Acute | 78 |
| Neurological Deficit | 19 |
| Nausea/Vomiting | 17 |
| Head Trauma | 15 |
| Hx of Migraine | 14 |
| Atypical/New Headache | 12 |
| Chronic Headache | 10 |
| Trauma | 10 |
| Malignancy | 8 |
| Thunderclap | 7 |
| VP Shunt | 7 |
| Brain Tumor | 6 |
| Hx of Intracranial Hemorrhage | 6 |
| Fever | 5 |
| Altered Mental Status | 4 |
| Cranial Surgery | 4 |
| Neck Pain | 4 |
| Coagulopathy | 3 |
| Hx of Aneurysm | 3 |
| Hydrocephalus | 3 |
| Rapid Increase in Headache Frequency | 3 |
| Abnormal Vital Signs/High Blood Pressure | 2 |

| Indication | Count |
|---|---|
| Loss of Consciousness | 2 |
| Normal Neurological Exam | 2 |
| Seizure | 2 |
| Vision Changes | 2 |
| Abscess/Encephalitis/Meningitis | 1 |
| Chiari Malformation | 1 |
| Connective Tissue Disorder | 1 |
| Coumadin | 1 |
| Endocarditis | 1 |
| Family Hx of Aneurysm | 1 |
| Family Hx of Brain tumor | 1 |
| GCS = 15 | 1 |
| HIV | 1 |
| Hx of AV Malformation | 1 |
| Immunocompromised | 1 |
| Lovenox | 1 |
| Metastases | 1 |
| Recent Lumbar Puncture | 1 |
| Sinusitis/Mastoiditis | 1 |
| Vertigo | 1 |

Hx – History, VP – Ventriculoperitoneal, GCS – Glasgow Coma Scale, HIV – Human Immunodeficiency Virus, AV – Arteriovenous

**FIGURES**

Figure 1: Study design diagram for patient selection for research objective 1

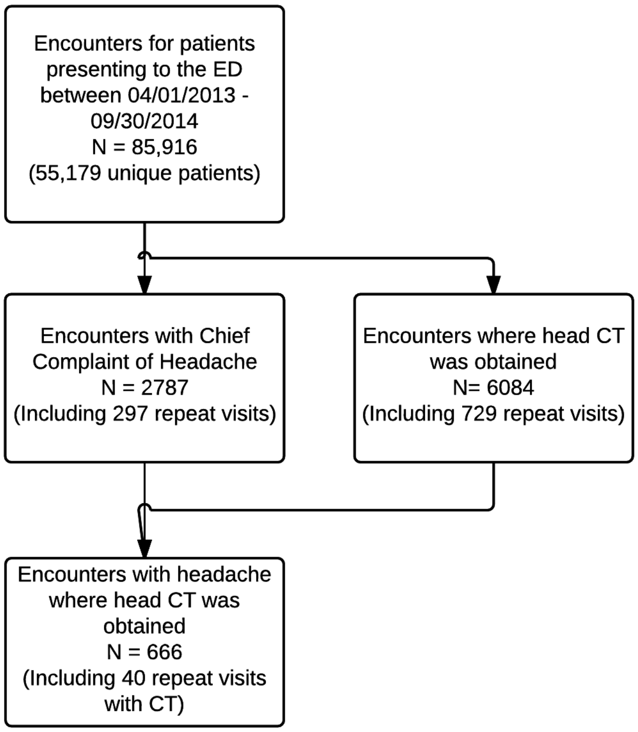


Figure 2: Box plots of count of concepts extracted from requisition indications compared to extracted Concept Unique Identifier (CUIs) in History of present illness notes completed and signed prior to order entry

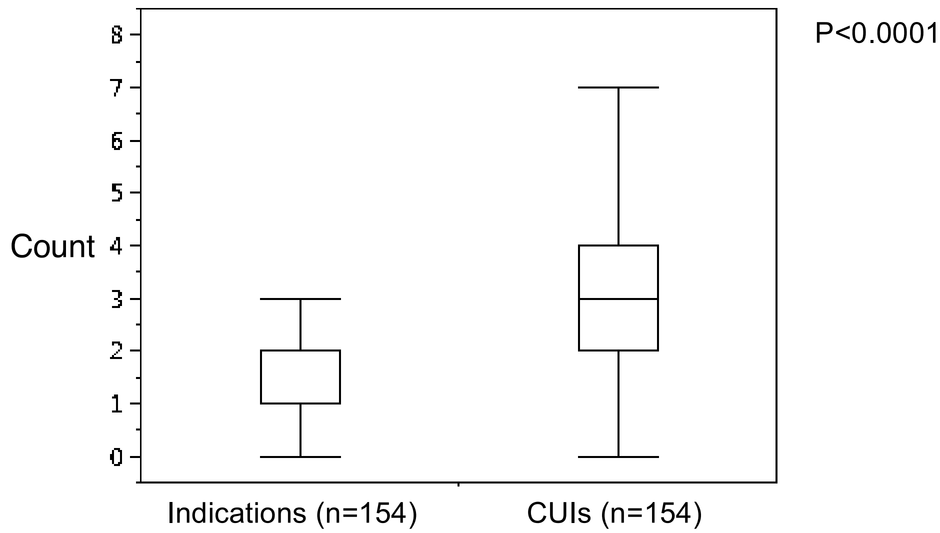
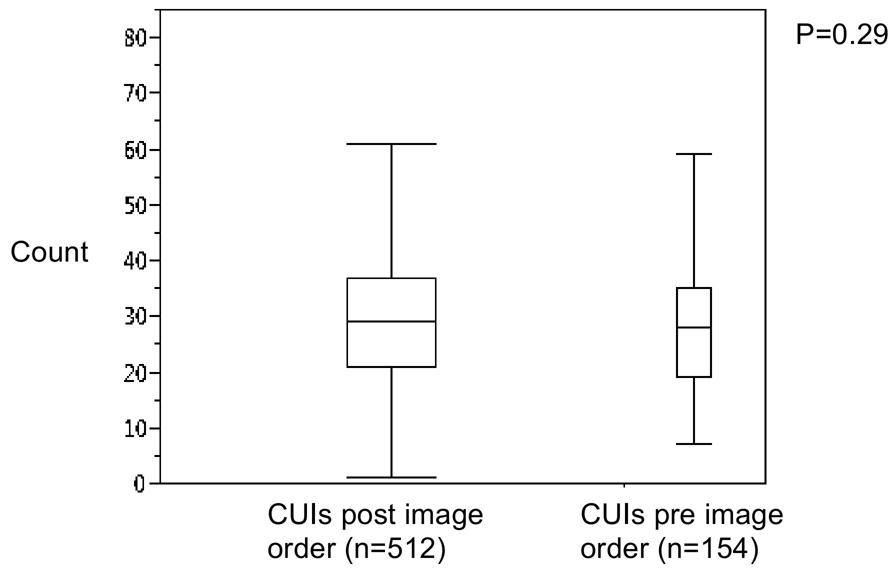
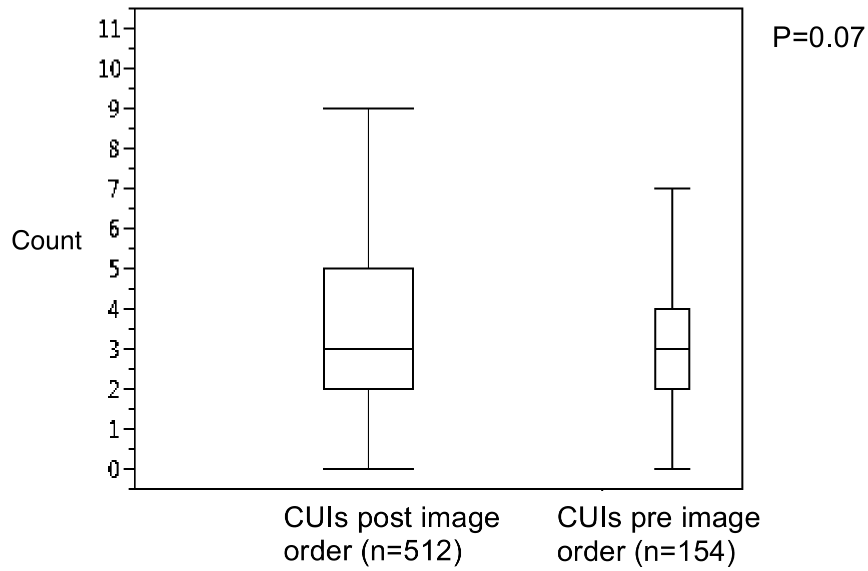


Figure 3: Box plots comparing total extracted concepts from History of present illness notes completed and signed after and before image order entry




CUI – Concept Unique Identifier

Figure 4: Box plots comparing extracted concepts relevant to headache from History of present illness notes completed and signed after and before image order entry




CUI – Concept Unique Identifier

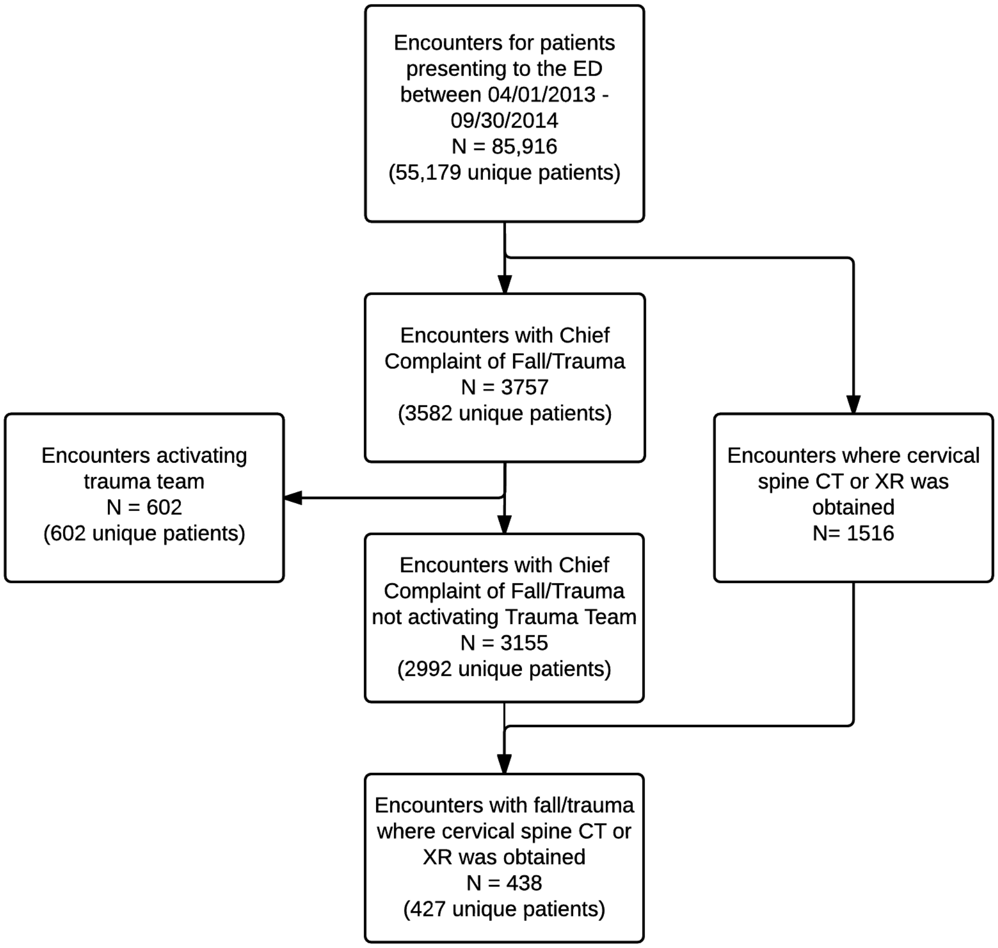
Figure 5: Word cloud of extracted concepts from History of present illness notes completed and signed before image order entry


Blue – Positive concepts; Red – Negated concepts; Size – relative frequency of concept adjusted by LN(count + 1). Frequency counts listed in Supplemental Table 1.

Figure 6: Word cloud of indications from image order requisitions


Size – relative frequency of concept adjusted by LN(count +1). Frequency counts listed in Supplemental Table 2.

Figure 7: Study design diagram for patient selection for research objective 2



Appendix 1: List of SNOMED CT Concept Unique Identifier (CUI) codes and terms determined to be important in evaluating a patient with headache when considering whether to obtain an imaging study

| CUI | Term |
|---|---|
| **C0149931** | Migraine |
| **C1276802** | Sudden onset |
| **C0521668** | Thunderclap headache |
| **C0205182** | Atypical |
| **C0016397** | Focal Infection |
| **C0009450** | Infectious disease |
| **C0015967** | Fever |
| **C0037199** | Sinusitis |
| **C0024904** | Mastoiditis |
| **C0271476** | Empyema of mastoid |
| **C0032285** | Pneumonia |
| **C0243026** | Sepsis |
| **C0278061** | Altered mental status |
| **C2316693** | Transient altered mental status |
| **C0036572** | Seizures |
| **C0522253** | Exertional headache |
| **C0019693** | HIV Infection |
| **C0021080** | Immunosuppression |
| **C0275531** | Immunosuppression-related infectious disease |
| **C0085393** | Immunocompromised host |

| CUI | Term |
| --- | --- |
| **C0547030** | Visual disturbance |
| **C0573983** | Nuchal pain |
| **C4041047** | Family hx of aneurysm of brain |
| **C2315869** | Family hx of aneurysm of artery |
| **C0003280** | Anticoagulant |
| **C0004057** | Aspirin |
| **C0070166** | Clopidogrel |
| **C0633084** | Plavix |
| **C0281875** | Illicit drug use |
| **C1318616** | History of recreational drug use |
| **C2711476** | Dependence on unknown drug |
| **C0728899** | Intoxication |
| **C0032343** | Poisoning |
| **C0600688** | Toxic effect |
| **C0394996** | Acute alcohol intoxication |
| **C0001969** | Alcohol intoxication |
| **C0085094** | Head trauma, closed |
| **C0043251** | Trauma |
| **C0018674** | Trauma, head |
| **C0751185** | Cough headache syndrome |
| **C0042293** | Valsalva maneuver |
| **C0541798** | Wakes and cannot sleep again |
| **C0007859** | Neck pain |

| CUI | Term |
|---|---|
| **C0151315** | Neck stiffness |
| **C0041657** | Loss of consciousness |
| **C2919620** | Witnessed syncope |
| **C0022680** | Polycystic kidney disease |
| **C0009782** | Connective tissue diseases |
| **C1306459** | Malignancy |
| **C0006826** | Cancer |
| **C0023895** | Liver disease |
| **C1458140** | Tendency to bleed |
| **C0005779** | Blood clotting disorder |
| **C2314995** | History of aneurysm |
| **C0475872** | History of subarachnoid hemorrhage |
| **C1997717** | History of cerebral hemorrhage |
| **C0475073** | Subarachnoid Hemorrhage |
| **C2937358** | Cerebral Parenchymal Hemorrhage |
| **C0007766** | Aneurysm, intracranial |
| **C0521654** | Neurological deficit |
| **C1821572** | Decreased level of consciousness |
| **C0025287** | Meningismus |
| **C0085584** | Encephalopathy |
| **C0014038** | Encephalitis |
| **C0030353** | Papilledema |
| **C0035317** | Retinal hemorrhage |

| CUI | Term |
|---|---|
| **C0178671** | Head and neck injury |
| **C0042963** | Vomiting |
| **C0007280** | Carotid bruit |
| **C2316225** | Chronic headache disorder |
| **C0234072** | Abnormal neurologic function |
| **C0699129** | Warfarin sodium |
| **C0542331** | Shunt |
| **C0010280** | Craniotomy |
| **C0195897** | Craniectomy |
| **C0023182** | CSF - Cerebrospinal fluid leak |
| **C0003803** | Chiari malformation |
| **C0549423** | Obstructive hydrocephalus |
| **C0003857** | Congenital AVM |
| **C1395545** | Vascular dissection |
| **C0340643** | Dissection of aorta |
| **C0026769** | Generalized multiple sclerosis |
| **C0724579** | Enoxaparin sodium |
| **C0042571** | Vertigo |
| **C0444793** | Position change |
| **C0034115** | Puncture and aspiration |
| **C2711782** | History of sickle cell anemia |
| **C0006142** | Breast cancer |
| **C0027627** | Metastases |

| CUI | Term |
| --- | --- |
| **C2939419** | Neoplasm, metastatic |
| **C0006118** | Brain tumor |
| **C0024299** | Lymphoma [disease/finding] |
| **C0475686** | History of Leukemia |
| **C0023470** | Myeloid leukemia - category |
| **C0026764** | Multiple myeloma |
| **C0002871** | Anemia |
| **C0040034** | Thrombocytopenia |
| **C0395959** | Pulsatile tinnitus |
| **C0028643** | Numbness |
| **C0085826** | Antiplatelet agent |
| **C0021081** | Immune suppressants |
| **C0021079** | Immunosuppressive therapy |
| **C0332835** | Transplanted organ |
| **C0231686** | Instability of gait |
| **C0002622** | Amnesia - memory loss |
| **C0001975** | Alcohol |
| **C0001175** | AIDS |
| **C0012569** | Double vision |
| **CL426668** | Blurring |
| **C0004093** | General weakness |
| **C0030554** | Paresthesia |
| **C0018989** | Unilateral paresis |

| CUI | Term |
|---|---|
| **C0018946** | Subdural hematoma |
| **C0038525** | Subarachnoid hemorrhage |
| **C0277803** | Normal vital signs |

## References


1 Sentinel Event Alert. 2015.www.jointcommission.org (accessed 11 Feb2016).

2 Boonn WW, Langlotz CP. Radiologist Use of and Perceived Need for Patient Data Access. *J Digit Imaging* 2009;**22**:357–62. doi:10.1007/s10278-008-9115-2

3 Obara P, Sevenster M, Travis A, *et al.* Evaluating the Referring Physician's Clinical History and Indication as a Means for Communicating Chronic Conditions That Are Pertinent at the Point of Radiologic Interpretation. *J Digit Imaging* 2015;**28**:272–82. doi:10.1007/s10278-014-9751-7

4 Leslie A, Jones AJ, Goddard PR. The influence of clinical information on the reporting of CT by radiologists. *Br J Radiol* 2000;**73**:1052–5. doi:10.1259/bjr.73.874.11271897

5 Centers for Disease Control and Prevention. Quick Stats: Annual Percentage of Emergency Department Visits With Selected Imaging Tests Ordered or Provided — National Hospital Ambulatory Medical Care Survey, United States, 2001-2010 [Internet]. 2013 Jun p. 455. Available from: http://www.cdc.gov/mmwr/preview/mmwrhtml/mm6222a6.htm.

6 Edlow JA, Panagos PD, Godwin SA, *et al.* Clinical Policy: Critical Issues in the Evaluation and Management of Adult Patients Presenting to the Emergency Department With Acute Headache. *Ann Emerg Med* 2008;**52**:407–36. doi:10.1016/j.annemergmed.2008.07.001

7 Choosing Wisely—An Initiative of the ABIM Foundation [Internet]. http://choosingwisely.org (accessed 11 Feb2016).

8 Savova GK, Masanz JJ, Ogren PV, *et al.* Mayo clinical Text Analysis and Knowledge Extraction System (cTAKES): architecture, component evaluation and applications. *J Am Med Inform Assoc* 2010;**17**:507–13. doi:10.1136/jamia.2009.001560

9 Garla VN, Brandt C. Ontology-guided feature engineering for clinical text classification. *J Biomed Inform* 2012;**45**:992–8. doi:10.1016/j.jbi.2012.04.010

10 Garla V, Re VL, Dorey-Stein Z, *et al.* The Yale cTAKES extensions for document classification: architecture and application. *J Am Med Inform Assoc* 2011;**18**:614–20. doi:10.1136/amiajnl-2011-000093

11 MetamorphoSys Help. 2009.https://www.nlm.nih.gov/research/umls/implementation_resources/metamorphosys/help.html (accessed 8 Feb2016).

12 National Cancer Informatics Program: Terminology. https://cbiit.nci.nih.gov/ncip/biomedical-informatics-resources/interoperability-and-semantics/terminology (accessed 4 Feb2016).

13 Cutrer FM. Evaluation of the adult with headache in the emergency department. In: UpToDate, Post TW (Ed).

14 Rothman RE, Keyl PM, McArthur JC, *et al.* A decision guideline for emergency department utilization of noncontrast head computed tomography in HIV-infected patients. *Acad Emerg Med Off J Soc Acad Emerg Med* 1999;**6**:1010–9.

15 Edlow JA, Caplan LR. Avoiding pitfalls in the diagnosis of subarachnoid hemorrhage. *N Engl J Med* 2000;**342**:29–36. doi:10.1056/NEJM200001063420106

16 Friedman BW, Lipton RB. Headache Emergencies: Diagnosis and Management. *Neurol Clin* 2012;**30**:43–59. doi:10.1016/j.ncl.2011.09.008

17 Swadron SP. Pitfalls in the Management of Headache in the Emergency Department. *Emerg Med Clin North Am* 2010;**28**:127–47. doi:10.1016/j.emc.2009.09.007

18 Practice parameter: the utility of neuroimaging in the evaluation of headache in patients with normal neurologic examinations (summary statement). Report of the Quality Standards Subcommittee of the American Academy of Neurology. *Neurology* 1994;**44**:1353–4.

19 Ramirez-Lassepas M, Espinosa CE, Cicero JJ, *et al.* Predictors of intracranial pathologic findings in patients who seek emergency care because of headache. *Arch Neurol* 1997;**54**:1506–9.

20 Locker TE, Thompson C, Rylance J, *et al.* The Utility of Clinical Features in Patients Presenting With Nontraumatic Headache: An Investigation of Adult Patients Attending an Emergency Department. *Headache J Head Face Pain* 2006;**46**:954–61. doi:10.1111/j.1526-4610.2006.00448.x

21 Perry JJ, Stiell IG, Sivilotti MLA, *et al.* High risk clinical characteristics for subarachnoid haemorrhage in patients with acute headache: prospective cohort study. *BMJ* 2010;**341**:c5204–c5204. doi:10.1136/bmj.c5204

22 Perry JJ, Stiell IG, Sivilotti MLA, *et al.* Clinical Decision Rules to Rule Out Subarachnoid Hemorrhage for Acute Headache. *JAMA* 2013;**310**:1248. doi:10.1001/jama.2013.278018

23 Dean NC, Jones BE, Ferraro JP, *et al.* Performance and utilization of an emergency department electronic screening tool for pneumonia. *JAMA Intern Med* 2013;**173**:699–701. doi:10.1001/jamainternmed.2013.3299

24 Celi LA, Marshall JD, Lai Y, *et al.* Disrupting Electronic Health Records Systems: The Next Generation. *JMIR Med Inform* 2015;**3**:e34. doi:10.2196/medinform.4192

25 Demner-Fushman D, Chapman WW, McDonald CJ. What can natural language processing do for clinical decision support? *J Biomed Inform* 2009;**42**:760–72. doi:10.1016/j.jbi.2009.08.007

26 Bates DW. Ten Commandments for Effective Clinical Decision Support: Making the Practice of Evidence-based Medicine a Reality. *J Am Med Inform Assoc* 2003;**10**:523–30. doi:10.1197/jamia.M1370

27 Khorasani R, Hentel K, Darer J, *et al.* Ten Commandments for Effective Clinical Decision Support for Imaging: Enabling Evidence-Based Practice to Improve Quality and Reduce Waste. *Am J Roentgenol* 2014;**203**:945–51. doi:10.2214/AJR.14.13134

28 Raja AS, Ip IK, Prevedello LM, *et al.* Effect of computerized clinical decision support on the use and yield of CT pulmonary angiography in the emergency department. *Radiology* 2012;**262**:468–74. doi:10.1148/radiol.11110951

29 Hoffman JR, Wolfson AB, Todd K, *et al.* Selective cervical spine radiography in blunt trauma: methodology of the National Emergency X-Radiography Utilization Study (NEXUS). *Ann Emerg Med* 1998;**32**:461–9.

30 Hoffman JR, Mower WR, Wolfson AB, *et al.* Validity of a Set of Clinical Criteria to Rule Out Injury to the Cervical Spine in Patients with Blunt Trauma. *N Engl J Med* 2000;**343**:94–9. doi:10.1056/NEJM200007133430203

31 Stiell IG. The Canadian C-Spine Rule for Radiography in Alert and Stable Trauma Patients. *JAMA* 2001;**286**:1841. doi:10.1001/jama.286.15.1841

32 Gupta A, Ip IK, Raja AS, *et al.* Effect of clinical decision support on documented guideline adherence for head CT in emergency department patients with mild traumatic brain injury. *J Am Med Inform Assoc* 2014;:amiajnl – 2013–002536. doi:10.1136/amiajnl-2013-002536

33 Lin C-P, Payne TH, Nichol WP, *et al.* Evaluating clinical decision support systems: monitoring CPOE order check override rates in the Department of Veterans Affairs' Computerized Patient Record System. *J Am Med Inform Assoc JAMIA* 2008;**15**:620–6. doi:10.1197/jamia.M2453

34 Sittig DF, Singh H. Electronic Health Records and National Patient-Safety Goals. *N Engl J Med* 2012;**367**:1854–60. doi:10.1056/NEJMsb1205420

35 Weiskopf NG, Weng C. Methods and dimensions of electronic health record data quality assessment: enabling reuse for clinical research. *J Am Med Inform Assoc* 2013;**20**:144–51. doi:10.1136/amiajnl-2011-000681