Research and Applications

Extracting seizure frequency from epilepsy clinic notes: a machine reading approach to natural language processing

Kevin Xie1,2, Ryan S. Gallagher2,3, Erin C. Conrad3, Chadric O. Garrick2, Steven N. Baldassano1,2, John M. Bernabei1,2, Peter D. Galer1,2,4, Nina J. Ghosn1,2, Adam S. Greenblatt3, Tara Jennings3, Alana Kornspun3, Catherine V. Kulick-Soper3, Jal M. Panchal1,2,5, Akash R. Pattnaik1,2, Brittany H. Scheid1,2, Danmeng Wei3, Micah Weitzman6, Ramya Muthukrishnan7, Joongwon Kim7, Brian Litt1,2,3, Colin A. Ellis2,3, and Dan Roth7

1Department of Bioengineering, School of Engineering and Applied Sciences, University of Pennsylvania, Philadelphia, Pennsylvania, USA, 2Center for Neuroengineering and Therapeutics, University of Pennsylvania, Philadelphia, Pennsylvania, USA, 3Department of Neurology, Penn Epilepsy Center, Perelman School of Medicine, University of Pennsylvania, Philadelphia, Pennsylvania, USA, 4Department of Biomedical and Health Informatics, Children’s Hospital of Philadelphia, Philadelphia, Pennsylvania, USA, 5The General Robotics, Automation, Sensing and Perception Laboratory, School of Engineering and Applied Sciences, University of Pennsylvania, Philadelphia, Pennsylvania, USA, 6Department of Electrical and Systems Engineering, School of Engineering and Applied Sciences, University of Pennsylvania, Philadelphia, Pennsylvania, USA, and 7Department of Computer and Information Science, School of Engineering and Applied Sciences, University of Pennsylvania, Philadelphia, Pennsylvania, USA

Colin A. Ellis and Dan Roth contributed equally to this work.
Corresponding Authors: Colin A. Ellis, MD, Department of Neurology, Penn Epilepsy Center, Perelman School of Medicine, University of Pennsylvania, 3400 Spruce Street, Philadelphia, PA 19104, USA; colin.ellis2@pennmedicine.upenn.edu

Received 26 November 2021; Revised 11 January 2022; Editorial Decision 27 January 2022; Accepted 8 February 2022

ABSTRACT

Objective: Seizure frequency and seizure freedom are among the most important outcome measures for patients with epilepsy. In this study, we aimed to automatically extract this clinical information from unstructured text in clinical notes. If successful, this could improve clinical decision-making in epilepsy patients and allow for rapid, large-scale retrospective research.

Materials and Methods: We developed a finetuning pipeline for pretrained neural models to classify patients as being seizure-free and to extract text containing their seizure frequency and date of last seizure from clinical notes. We annotated 1000 notes for use as training and testing data and determined how well 3 pretrained neural models, BERT, RoBERTa, and Bio_ClinicalBERT, could identify and extract the desired information after finetuning.

Results: The finetuned models (BERTFT, Bio_ClinicalBERTFT, and RoBERTaFT) achieved near-human performance when classifying patients as seizure free, with BERTFT and Bio_ClinicalBERTFT achieving accuracy scores over 80%. All 3 models also achieved human performance when extracting seizure frequency and date of last seizure, with overall F1 scores over 0.80. The best combination of models was Bio_ClinicalBERTFT for classification, and RoBERTaFT for text extraction. Most of the gains in performance due to finetuning required roughly 70 annotated notes.

© The Author(s) 2022. Published by Oxford University Press on behalf of the American Medical Informatics Association. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.
INTRODUCTION

The electronic health record (EHR) is an ever-growing resource of documents created by healthcare providers to monitor the well-being of patients. Among such documents are progress notes, which are unstructured or minimally structured free-text documents that clinicians use to record interactions with patients. Progress notes contain the patient’s medication list, general well-being, diagnoses, treatments, and disease progression.1 The EHR is a source of information and data for large-scale retrospective clinical research2–4; instead of following cohorts prospectively for extended periods of time, researchers can look backwards through the EHR using information gathered during patient visits to answer clinical questions. Such retrospective studies may also be cheaper to conduct than the current costly prospective standard of research,5 which often costs thousands of dollars per subject.

However, manually extracting information from the EHR can be time consuming and impractical. Automated text mining methods from natural language processing (NLP), a field of computer science dedicated toward teaching machines to read and comprehend human language, have attempted to mitigate this problem. Recent strides in NLP have created pretrained language models, based largely on the Transformer architecture, with unprecedented abilities to understand unstructured text and generalize across a wide range of tasks and domains.6–10 Transfer learning is a key advantage of these models, which are initially pretrained on a large text corpus to obtain a general understanding of language. They can then be finetuned on small datasets to be adapted toward specific tasks or domains. Already, such models have shown strong flexibility and accuracy in specialized domains. For example, the Bio_ClinicalBERT model demonstrated high accuracy and F1 scores for various clinical NLP benchmarking tasks.11

In the clinical care of patients with epilepsy, among the most important markers of clinical severity and response to treatment are (1) the presence or absence of seizures (seizure freedom) and (2) the frequency of seizures over a given time, generally within the past year or since the last office visit. These outcome measures are challenging for automated extraction from text. For example, paroxysmal events at irregular intervals with dynamic temporal components preclude simple static phenotypic classification of patients. In this study, we developed a novel NLP pipeline to automatically extract seizure freedom and seizure frequency from clinical notes at the University of Pennsylvania Health System (UPHS), validated against human annotations. Our novel pipeline uses a combination of existing pretrained models, publicly available finetuning tools, and a relatively small amount of task-specific annotation; we expect that it will be generalizable to a wide range of research questions that require extracting and classifying text from clinical notes.

MATERIALS AND METHODS

Document curation

This retrospective study was approved by the Institutional Review Board of the University of Pennsylvania with a waiver of informed consent. We obtained nearly 79,000 progress notes for patients with epilepsy who visited UPHS between January 1, 2015 and December 31, 2018. We filtered for notes authored by 8 epilepsy specialists, and extracted text from these notes as “paragraphs” to improve the probability that the text involved epileptic events; we truncated these paragraphs to better fit within the maximum sequence length of the models (512 tokens) and appended the date each note was written to the front of each paragraph (see Supplementary Methods). We were interested in identifying patient seizure freedom and extracting their seizure frequencies. We formulated this problem as a question-answering task, where a model attempts to answer a series of questions given a context. From these paragraphs, we asked 3 questions (Table 1): (Q1) “has the patient had recent seizures,” (Q2) “how often does the patient have seizures,” and (Q3) “when was the patient’s most recent seizure.” For question 1, we defined “recent seizures” as occurring either (1) since the last office visit, or (2) in the 1 year before the note was written, whichever was more recent. Note that these questions require distinct paradigms: the first classifies patients as being seizure-free using all available information in the note, while the latter 2 extract the span of text in the paragraph that best answers them. Additionally, an answer to any or all of these questions may not exist in a given paragraph.

Annotation

We recruited 15 annotators to collectively mark 1000 paragraphs in a manner that answered the 3 questions. This number of documents was chosen to balance annotation time with having sufficient dataset size for model training and evaluation. Documents were chosen randomly but with a uniform distribution across the 8 note authors, such that each author wrote 125 paragraphs, to evenly capture their representative styles. Annotations were performed on the INCEPTION platform.12 Our 15 annotators consisted of 7 clinicians (epilepsy nurse practitioners, neurology residents, epilepsy fellows, and attending physicians), and 8 nonclinicians (graduate students or personnel working in a lab focused on epilepsy-related research). We created 5 annotation groups, each with 200 unique paragraphs. We

Table 1. Questions and corresponding task paradigm for the question-answering task

| Question                                      | Task paradigm |
|-----------------------------------------------|---------------|
| Q1: “Has the patient had recent seizures?”   | Classification|
| Q2: “How often does the patient have seizures?” | Text extraction |
| Q3: “When was the patient’s most recent seizure?” | Text extraction |
divided our annotators between these groups such that each group had at least 1 clinician and at least 1 nonclinician annotator, and that each document would have 3 independent sets of annotations.

Once all annotations were completed, annotations were merged and adjudicated. Disagreements between annotations for each paragraph were settled in most cases by majority voting between the annotations. On occasions where no majority could be reached, 2 of the authors (KX and CAE) together manually adjudicated the annotation. The 5 groups of 200 adjudicated paragraphs were merged into a single dataset of 1000 paragraphs defined as the “ground truth” annotations.

We calculated interrater reliability among the human annotators using Cohen’s Kappa (κ) for the classification question,\(^\text{14}\) and F\(_1\) score for the text extraction questions. \(\kappa\) measures the observed agreement between annotators, offset by their expected agreement due to chance. By convention, a \(\kappa\) above 0.81 indicates “near perfect” agreement.\(^\text{15}\) The F\(_1\) score measures the amount of text overlap; an F\(_1\) score of 1.0 indicates the spans of text are identical, whereas an F\(_1\) of 0 indicates no intersection. We calculated the F\(_1\) score in 2 ways: a paired F\(_1\), which shows annotator consistency when 2 annotators agree on some amount of text, and an overall F\(_1\), which includes all annotations for a particular question in each note.

Model finetuning and evaluation
We randomly split the annotated paragraphs into a training set of 700 paragraphs, and a testing set of 300 paragraphs. We targeted 3 models: the original BERT,\(^\text{9}\) Bio_ClinicalBERT,\(^\text{12}\) which has additional pretraining on clinical and biomedical texts, and RoBERTa,\(^\text{16}\) a version of BERT with improved pretraining objectives, including dynamic masking without next-sentence-prediction over significantly more data, and better hyperparameters, such as a larger batch size and a larger tokenization vocabulary. We selected BERT to serve as a useful baseline, and Bio_ClinicalBERT and RoBERTa due to its improved performance on clinical benchmarking tasks, and its consistently high performance across several general NLP tasks, respectively. Because the classification question (Q1) and text extraction questions (Q2 and Q3) constituted distinct task paradigms, they required 2 separate models, 1 for each type of task.

Our fine-tuning pipeline (Figure 1) followed the insights of Han and Eisenstein\(^\text{17,18}\): using a single pretrained model, we first performed unsupervised domain adaptation with masked language modeling (MLM) using the 78 000 progress notes that were not selected for annotation. We then performed task-specific finetuning with the resultant model in 2 separate instances on publicly available English datasets—I on BoolQ3L for the classification task,\(^\text{19}\) and the other on SQuADv2 for the text extraction task,\(^\text{20}\) resulting in a pair of models. We concluded model training with supervised finetuning on the training set of human-annotated medical notes. The order of our pipeline’s steps followed and combined the order of finetuning steps used in the 2 aforementioned studies.\(^\text{17,18}\) We repeated this pipeline 5 times for each of the 3 starting models with a set of arbitrarily chosen seeds to allow for estimates of the variability of each model’s performance. We denote the models finetuned using the full pipeline as BERT\(_\text{FT}\), Bio_ClinicalBERT\(_\text{FT}\), and RoBERTa\(_\text{FT}\), for the models finetuned from BERT, Bio_ClinicalBERT, and RoBERTa, respectively. We performed ablation studies by removing each step of our pipeline (1 at a time while leaving the other steps unchanged) to evaluate their individual impacts on model performance; as before, we used 5 arbitrarily chosen seeds for each ablation experiment.

We evaluated the performance relative to the ground truth annotations using the accuracy metric for the classification question (defined as correct classifications divided by total classifications), and the F\(_1\) text overlap score for the text extraction questions. As before, the F\(_1\) score is based purely on the overlap between spans of text. We set the F\(_1\) and accuracy scores so that they lie on the same 0–1 scale. We used Huggingface Transformers,\(^\text{21}\) a Python library for neural NLP models, to perform finetuning and used their evaluation methods or the official SQuADv2 evaluation script when appropriate to determine the model’s performance.\(^\text{20}\) For all finetuning steps, we used Huggingface’s default and supplied hyperparameters and

---

**Figure 1.** Schematic methods detailing the annotation and finetuning pipeline. Pretrained language models are finetuned using masked language modeling by exposing them to 78 000 unannotated clinical notes; task specific datasets (SQuADv2 and BoolQ3L); and the training set of annotated notes. This process was repeated for 5 different seeds.
did not perform any hyperparameter optimization. We set the maximum sequence length of the 3 models to 512 tokens to capture as much information at once as possible. We assessed human annotator correctness by comparing each individual's annotations against the final ground truth annotations. Because the NLP models made 1 prediction per question per note, we selected the annotation closest in proximity to the ground truth annotation to make a direct comparison in cases where a human annotator made more than 1 annotation for a given question. If multiple ground truths existed for a given question, the annotation with the highest similarity to any of the ground truths was selected.

RESULTS

Interrater reliability and ground truth annotations

For the classification question, agreement among human annotators was consistently in the “near perfect” range (average pairwise $\kappa = 0.82$, with 13/17 [76%] pairs having $\kappa > 0.8$). For the text extraction questions, the paired $F_1$ had an average pairwise value of 0.79 when annotators identified overlapping spans of text. The overall $F_1$, which considered all annotations per note, had an average pairwise value 0.44 (Figure 2). We found that there was no difference in human annotator correctness between clinician and nonclinician annotators.

The final dataset consisted of ground truth annotations for 1000 notes. For the classification question (Q1), 61.8% of notes were classified as having recent seizures, 30.3% as not having recent seizures, and 7.8% had no answer. For the text extraction questions, 35.5% of notes contained a statement of seizure frequency (Q2) and 49.5% of notes contained a statement of most recent seizure occurrence (Q3).

Evaluating model performance

Figure 3 shows the performance of each of the 3 fine-tuned models as well as human performance on each of our question-answering tasks, compared with ground truth annotations. For the classification question (Q1), Bio_ClinicalBERTFT and BERTFT each showed strong and robust performances across 5 trials, with Bio_ClinicalBERTFT achieving the highest median (0.837) accuracy, with a maximum of 0.863. RoBERTaFT showed more variability across trials and the lowest median accuracy (0.749). We performed 2-sided Mann-Whitney $U$ tests comparing the ablation experiments to the full finetuning pipeline with the null hypothesis that the ablated models and the full model have equivalent performance. For the classification question, we rejected the null hypothesis for the models finetuned without MLM or annotations (P values = .021 and .008, respectively), indicating that those 2 factors were significant contributors to the models’ performance. For the seizure frequency question, we found that only the annotations had a significant contribution to the models’ performance (P value = .0079). For the most recent occurrence question, both MLM and annotations were significant contributors to model performance (P values = .032 and .008, respectively; Figure 4). Overall, it is evi-

![Figure 2](https://academic.oup.com/jamia/advance-article/doi/10.1093/jamia/ocac018/6534112)

**Figure 2.** Mean intragroup Cohen’s $\kappa$ and $F_1$ scores with 95% confidence intervals. Annotators within each group were compared pairwise and demonstrated high agreement across all groups. $\kappa$ was calculated using annotator classification values (Q1), $F_1$ was calculated using annotator text extractions (Q2 and Q3).
dent that the annotated training dataset was the most significant step in the training pipeline, and that the MLM step was occasionally helpful.

We next asked how much annotated training data were ultimately required. We split the annotated training dataset into cumulative tenths and applied the fine-tuning pipeline with 5 seeds using these subdatasets on Bio_ClinicalBERT and RoBERTa for classification and text extraction, respectively. Using the first 10% of the training dataset (ie, 70 annotated notes), we achieved 82.7% of the final accuracy for the classification question, and 91.0% and 90.6% of the final F1 scores for the 2 text extraction questions (Figure 5).

We repeated the above analyses after stratifying notes according to whether an answer existed to the text extraction questions (Q2 and Q3). We found that all language models were very accurate at identifying notes where no answer existed. In notes where an answer existed, performance was lower, although this was true for both the NLP models and the human annotators, with the models performing better than most human annotators (see Supplementary Results).

Finally, we manually reviewed instances where our model failed to predict the correct classification or failed to extract the correct span of text and we identified patterns among the errors. We analyzed the predictions of Bio_ClinicalBERTFT for classification, and RoBERTaFT for text extraction, both with the same best overall seed. We found that the leading cause of errors was due to too much irrelevant information, such as outdated seizure-related information and/or information unrelated to epilepsy in the paragraph, which resulted in the model becoming “confused,” and selecting, for example, an outdated seizure frequency. Additionally, we found that the models had trouble performing higher-order logic, including temporal reasoning. For example, the model had trouble classifying paragraphs that mentioned the patient having an event on a specific date, but being seizure-free from a more recent date, for example, “The patient had a seizure cluster on 4/13. They have been seizure-free since May.” The model also failed to perform implicit semantic reasoning; for example, the statement “the patient has been seizure-free since June” was interpreted by human annotators to mean that

![Human vs. Machine Performance on Extracting Clinical Information](https://academic.oup.com/jamia/advance-article/doi/10.1093/jamia/ocac018/6534112)

![Results of Ablation Studies](https://academic.oup.com/jamia/advance-article/doi/10.1093/jamia/ocac018/6534112)
the patient’s most recent seizure was in June. However, the model consistently failed to identify such statements as indicating a patient’s last event (Q3). Overall, it is evident that many of the prediction errors occurred in an understandable and nonrandom fashion (Table 2).

**DISCUSSION**

In this work, we developed a finetuning pipeline for NLP language models to improve their understanding of clinical notes for patients with seizures. We demonstrated that models finetuned using these methods can accurately extract seizure-related information from epilepsy notes to a high degree of correctness, rivaling that of a human. We identified consistent patterns of errors in our models and determined how each step of our finetuning pipeline helped to improve the models’ performance. Finally, we note that our methods can be used to answer different questions with minimal amounts of new data.

Our findings demonstrate the ability of machine systems to understand medical text practically and accurately. Our models can be used to support clinical decision-making by rapidly extracting important markers of epilepsy severity and treatment response from unstructured patient histories. Additionally, our generalizable pipeline can be used to conduct retrospective studies, at scale, across a wide range of clinical research questions in a fraction of the time and at a fraction of the cost required for prospective studies.

| Reason for consistent errors | Number of errors |
|------------------------------|------------------|
| Too much historical or irrelevant information | 44  18  8  18 |
| • For example, “In 2002 they began having convulsions, with frequency 3/month.” | 8  8  0  0 |
| • For example, “Patient with history of coronary artery disease… stent thrombosis, prostate cancer… readmitted after a fall… worsening subdural hematoma and rightward subfalcine herniation…” | 10  1  7  2 |
| Many relevant events with different information | | |
| • For example, “No seizures with loss of awareness since last visit. Continued probable simple partial seizures frequently.” | | |
| Identified irrelevant phenomena or failed to identify relevant phenomena from symptoms | | |
| • For example, “At least daily stomach spasms” | 3  0  3  0 |
| Unusual time anchor | | |
| • For example, “Occur on the first day of their menses.” | 11  9  0  2 |
| Temporal reasoning | | |
| • For example, “3 months ago, they had three seizures in July. No seizure since that time.” | 6  0  1  5 |
| Semantic reasoning | | |
| • For example, “… seizure free for the past 3 months.” | | |
Among human annotators, we found excellent agreement for the classification question, but poorer agreement overall for the text extraction questions. However, because we triple-annotated all notes and used majority adjudication in most cases, the paired F1 score gives a meaningful estimate of the reliability of annotations given that 2 annotators selected similar text spans. The lower F1 values when accounting for all annotations indicates that double or triple-annotating notes is still preferable because individual annotations in isolation have only modest interrater reliability. Additionally, our ground truth annotations were derived from human annotations. Therefore, they were not independent, and our method for estimating human performance (by comparing each individual annotator to the final ground truth) was biased in favor of overestimating human performance. Still, it was important to have a baseline against which to measure the performance of our models, and makes it even more impressive that the models (which were independent of the ground truth annotations) performed comparably to human annotators.

Our experiments also showed that the language models fine-tuned under our pipeline can achieve near-human and human-like performance on clinically meaningful epilepsy-related tasks. We found the best performing combination of models to be BioClinicalBERT and RoBERTa for text classification and text extraction, respectively. We observed that model performance on the classification question was slightly worse than human performance (although the model was still quite accurate), and model performance on the text extraction questions was equivalent to human performance. We hypothesize that this discrepancy may be in part because of the more complex logical reasoning required for the classification task. For example, if a note says “the last seizure occurred in June 2015,” it requires no inference to extract this text as the answer to Question 3, “When was the patient’s most recent seizure?” Meanwhile, correctly classifying the patient as seizure-free (Question 1, “Has the patient had recent seizures?” = no) requires knowledge of when the note was written, whether that date is more than 1 year after June 2015, and that 1 year is the criteria for a recent seizure. Previous work has shown that logical reasoning and temporal reasoning remain challenging for language models.

Such high performances on clinical datasets have been seen in other studies, though on different datasets and tasks. For example, Alsentzer et al used Transformer Models to achieve 82.7% accuracy on the MedNLI dataset, which measures how well a model can infer relationships between a hypothesis and premise using clinical texts. Additionally, both Alsentzer et al and Yang et al used Transformers to achieve F1 scores between 75 and 95 on various i2b2 and/or n2c2 clinical challenges. Previous work has also been done to apply NLP to epilepsy clinical notes: Fonferko et al used a rules-based NLP method to extract seizure frequency, among other information, from 200 clinical letters, achieving an F1 score of 66% on a per-item basis and 72% on a per-letter (ie, per-note) basis. Our methods differed from theirs in several aspects, especially in the manual steps required. In addition to preparing their data, they used manually coded rules for detecting statements of seizure frequency and large dictionaries of search terms to handle the intricacies of language and the various ways that seizure frequency can be represented in the text. In contrast, our manual efforts were confined solely to create and annotate our data. The language model then used that data to learn and understand the language in a more generalizable fashion. It is also important to note that the F1 scores reported in our and other studies may measure performance differently, depending on the NLP task and method, limiting direct comparisons between studies.

The findings of our ablation studies contrast with some of the literature. Han and Eisenstein, which inspired our pipeline, combined unsupervised domain adaptation with supervised task adaptation to improve BERT’s performance on sequence tagging in difficult domains. They devised 3 BERT models—a frozen BERT baseline, a task-tuned BERT, and a BERT with both domain tuning and task tuning. They found that sequentially adding these finetuning steps improved model performance over the baseline. Meanwhile, Soni and Roberts found that using SQuAD as an intermediate dataset improved clinical question answering performance for several models. In contrast, we found that only domain tuning and the annotated training set proved to be helpful, and only the annotations proved to be critical to model performance. Task tuning using intermediate datasets had no significant impact on the final performance of our models.

Our study does have some limitations. Our clinical notes are sourced from a single healthcare center and as such, the generalizability of our results to other centers is unknown and should be tested in future research. Similarly, we annotated, trained, and tested on specific neurology notes; our model may experience decreased performance when applied to notes from other departments. However, these problems can be solved with additional finetuning on a small dataset sourced from either the new institution or department, in the manner that we have described within this article. Additionally, our choice in models was constrained by the limitations of our 16 GB Nvidia P100 GPU. This prevented us from using different, larger models, such as Longformer, which has been found to outperform RoBERTa on long document tasks. This problem can be resolved by using a more powerful GPU in the future.

Our definition of seizure freedom (since last office visit or within 1 year) was also pragmatic, and reflects clinical practice for measuring this outcome measure, but from a machine learning perspective was arbitrary and may have affected the accuracy of our classification models. We also captured and lumped together the frequency of all types of seizures. For clinical purposes, some types of seizures are more severe (eg, bilateral tonic-clonic convulsions) and may require different clinical management than milder types (eg, focal aware “auras,” or myoclonic jerks). For patients with multiple types of seizures, extracting different frequency information for different seizure types should be addressed in future research. Additionally, copy-and-pasted information, a challenge for current electronic medical record systems, sometimes led to internally contradictory text within a single note. These are inherent challenges in NLP of free-text medical notes and will remain a challenge until medical record systems further constrain data entry or capture clinical data in more discrete, minable forms instead of prose text.

In the future, we hope to use our model to extract seizure freedom and seizure frequency data from clinical notes in real-time practice to improve clinical decision-making. We also plan to perform large-scale retrospective epilepsy research using data from UPHS and potentially from collaborating centers with the push of a button.

CONCLUSION

In conclusion, our novel NLP pipeline allowed models to extract clinically important outcome measures, seizure freedom, and seizure frequency for patients with epilepsy, with accuracies comparable to that of human annotators. This tool will enable investigators to mine outcome data from clinical note text at scale to facilitate clinical research and decision-making. The amount of training data re-
required to fine-tune the model was smaller than expected, suggesting that this tool can be adapted to other applications in the future with modest preparation.

FUNDING
This research was funded by the National Institute of Neurological Disorders and Stroke 1DP1 OD029758; by the Mirowski Family Foundation; and by contributions from Jonathan and Bonnie Rothberg. CAE is supported by the National Institute of Neurological Disorders and Stroke of the National Institutes of Health Award Number K23NS121520; by the American Academy of Neurology Susan S. Spencer Clinical Research Training Scholarship; and by the Mirowski Family Foundation. DR’s work was partially funded by the Office of Naval Research Contract N00014-19-1-2620.

AUTHOR CONTRIBUTIONS
KX, RSG, SNB, BL, CAE, and DR conceived, designed, and/or implemented the study; KX, RSG, SNB, MW, RM, JK, BL, CAE, and DR implemented initial investigations and experiments; KX, RSG, ECC, and CAE developed the annotation protocol of the study and performed pilot annotation studies; KX, ECC, COG, JMB, PDG, NJG, ASG, TJ, AK, CVK, JMP, ARP, BHS, DW, and CAE performed annotations; KX and CAE adjudicated annotations; KX, COG, and CAE analyzed and interpreted the data from the study; KX, RSG, BL, CAE, and DR drafted and edited the article.

SUPPLEMENTARY MATERIAL
Supplementary material is available at Journal of the American Medical Informatics Association online.

CONFLICT OF INTEREST STATEMENT
None declared.

DATA AVAILABILITY
The clinical data in this study cannot be publicly shared due to patient privacy concerns. However, our code is available on Github at https://github.com/penn-cnt/Extracting-Clinical-Information-From-Epilepsy-Clinic-Notes. We also provide a Zenodo DOI for our code at: https://doi.org/10.5281/zenodo.5838235. Our models can be accessed through the Huggingface Hub under the names: CNT-UPenn/Bio_ClinicalBERT_for_seizureFreedom_classification and CNT-UPenn/RobERTa_for_seizureFrequency_QA.

REFERENCES
1. Ehrenstein V, Kharraz H, Lehmahn H, et al. Obtaining Data From Electronic Health Records. Agency for Healthcare Research and Quality (US); 2019. https://www.ncbi.nlm.nih.gov/books/NBK551878/. Accessed October 22, 2021.
2. Casey JA, Schwartz BS, Stewart WF, et al. Using electronic health records for population health research: a review of methods and applications. Am J Prev Public Health 2016; 37: 61–81.
3. Cowie MR, Blomster JI, Curtis LH, et al. Electronic health records to facilitate clinical research. Clin Res Cardiol 2017; 106 (1): 1–9.
4. Lee S, Xu Y, D Apos Souza AG, et al. Unlocking the potential of electronic health records for health research. Int J Popul Data Sci 2020; 5 (1): 1123.
5. Wright JR, Levine MN. Researching the cost of research. J Clin Oncol 2003; 21 (22): 4081–2.
6. Emanuel EJ, Schnipper LE, Kamin DY, et al. The costs of conducting clinical research. J Clin Oncol 2003; 21 (22): 4145–50.
7. Song JW, Chung KC. Observational studies: cohort and case-control studies. Plast Reconstr Surg 2010; 126 (6): 2234–42.
8. Toledano MB, Smith RK, Brook JP, et al. How to establish and follow up a large prospective cohort study in the 21st century - lessons from UK COSMOS. PLoS One 2015; 10 (7): e0131521.
9. Devlin J, Chang M-W, Lee K, et al. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. In: Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers). Minneapolis, MN: Association for Computational Linguistics; 2019: 4171–86.
10. Chalkidis I, Fergadiotis M, Malakasiotis P, et al. LEGAL-BERT: The Muppets straight out of Law School. In: Findings of the Association for Computational Linguistics: EMNLP 2020. Online: Association for Computational Linguistics; 2020: 2898–904.
11. Vaswani A, Shazeer N, Parmar N, et al. Attention is All you Need. In: Proceedings of the 31st International Conference on Neural Information Processing Systems. Red Hook, NY: Curran Associates Inc; 2017: 6000–10.
12. Alsentzer E, Murphy J, Boag W, et al. Publicly available clinical BERT embeddings. In: Proceedings of the 2nd Clinical Natural Language Processing Workshop. Minneapolis, MN: Association for Computational Linguistics; 2019: 72–8.
13. Klie J-C, Bugert M, Boulois B, et al. The INCEpTION Platform: machine-assisted and knowledge-oriented interactive annotation. In: Proceedings of the 27th International Conference on Computational Linguistics: System Demonstrations. Santa Fe, NM: Association for Computational Linguistics; 2018: 5–9. https://aclanthology.org/C18-2002. Accessed October 22, 2021.
14. Cohen J. A coefficient of agreement for nominal scales. Educ Psychol Meas 1960; 20 (1): 37–46.
15. McHugh ML. Interrater reliability: the kappa statistic. Biochem Med 2012; 22: 276–82.
16. Liu Y, Ott M, Goyal N, et al. RoBERTa: A Robustly Optimized BERT Pretraining Approach. ArXiv190711692 Cs: Published Online First: July 26, 2019. http://arxiv.org/abs/1907.11692. Accessed October 22, 2021.
17. Han X, Eisenstein J. Unsupervised domain adaptation of contextualized embeddings for sequence labeling. In: Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP). Hong Kong, China: Association for Computational Linguistics; 2019: 4238–48.
18. Sotomi S, Roberts K. Evaluation of Dataset Selection for Pre-Training and Fine-Tuning Transformer Language Models for Clinical Question Answering. In: Proceedings of the 12th Language Resources and Evaluation Conference. Marseille, France: European Language Resources Association; 2020: 5532–8. https://aclanthology.org/2020.lrec-1.679. Accessed October 22, 2021.
19. Suleen E, Hay J, Roth D. Do We Know What We Don't Know? Studying Unanswerable Questions beyond SQuAD 2.0. In: Findings of the Association for Computational Linguistics: EMNLP 2021. Punta Cana, Dominican Republic: Association for Computational Linguistics; 2021: 4543–8. https://aclanthology.org/2021.findings-emnlp.385. Accessed November 8, 2021.
20. Rajpurkar P, Ju R, Liang P. Know What You Don't Know: Unanswerable Questions for SQuAD. In: Proceedings of the 56th Annual Meeting of the Association for Computational Linguistics (Volume 2: Short Papers). Melbourne, Australia: Association for Computational Linguistics; 2018: 784–9.
21. Wolf T, Debut L, Sanh V, et al. Transformers: State-of-the-Art Natural Language Processing. In: Proceedings of the 2020 Conference on Empirical Methods in Natural Language Processing: System Demonstrations. Online: Association for Computational Linguistics; 2020: 38–45.
22. Zhou B, Khashabi D, Ning Q, et al. “Going on a vacation” takes longer than “Going for a walk”: A Study of Temporal Commonsense Understanding. In: Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Confer-
ence on Natural Language Processing (EMNLP-IJCNLP). Hong Kong, China: Association for Computational Linguistics; 2019: 3363–9.

23. Vashishtha S, Poliak A, Lal YK, et al. Temporal Reasoning in Natural Language Inference. In: Findings of the Association for Computational Linguistics: EMNLP 2020. Online: Association for Computational Linguistics; 2020: 4070–8.

24. Yu W, Jiang Z, Dong Y, et al. ReClor: A Reading Comprehension Dataset Requiring Logical Reasoning. 2020. https://iclr.cc/virtual_2020/poster_HJgJrT4tvB.html. Accessed October 22, 2021.

25. Liu J, Cui L, Liu H, et al. LogiQA: A Challenge Dataset for Machine Reading Comprehension with Logical Reasoning. In: Proceedings of the Twenty-Ninth International Joint Conference on Artificial Intelligence. Yokohama, Japan: International Joint Conferences on Artificial Intelligence Organization; 2020: 3622–8.

26. Liu H, Cui L, Liu J, et al. Natural language inference in context - investigating contextual reasoning over long texts. Proc AAAI Conf Artif Intell 2021; 35: 13388–96.

27. Helwe C, Clavel C, Suchanek FM. Reasoning with Transformer-based Models: Deep Learning, but Shallow Reasoning. 2021. https://www.akbc.ws/2021/assets/pdfs/OzpWrgtF5_.pdf. Accessed October 22, 2021.

28. Romanov A, Shivade C. Lessons from Natural Language Inference in the Clinical Domain. In: Proceedings of the 2018 Conference on Empirical Methods in Natural Language Processing. Brussels, Belgium: Association for Computational Linguistics; 2018: 1586–96.

29. Yang X, Bian J, Hogan WR, et al. Clinical concept extraction using transformers. J Am Med Inform Assoc 2020; 27 (12): 1935–42.

30. Fonferko-Shadrach B, Lacey AS, Roberts A, et al. Using natural language processing to extract structured epilepsy data from unstructured clinic letters: development and validation of the ExECT (extraction of epilepsy clinical text) system. BMJ Open 2019; 9 (4): e023232.

31. Beltagy I, Peters ME, Cohan A. Longformer: The Long-Document Transformer. ArXiv200405150 Cs. Published Online First: December 2, 2020. http://arxiv.org/abs/2004.05150 Accessed December 29, 2021.