



Classification Models For Predicting Inflammatory Bowel Disease Healthcare Utilization

Dmitriy Babichenko¹^a, Behnam Rahdari¹^b, Ben Stein¹, Suraj Subramanian¹, Claudia Ramos Rivers², Gong Tang³, and David Binion²

¹*School of Computing and Information, University of Pittsburgh, Pittsburgh, PA*

²*School of Public Health, University of Pittsburgh, Pittsburgh, PA*

³*School of Medicine, University of Pittsburgh, Pittsburgh, PA*
dmb72@pitt.edu

Keywords: Inflammatory bowel disease, Healthcare utilization, Machine learning, Classification, Deep learning, Clinical decision support systems

Abstract: **Objective.** Inflammatory Bowel Disorders (IBD) is a group of gastric disorders that include well-known maladies such as Crohn's disease and Ulcerative Colitis (UC), as well as a number of other gastric disorders that are not well classified. Subgroups of patients contribute disproportionately to treatment costs. This work aims to create and evaluate machine learning models designed to use demographic and clinical predictors of IBD to predict which patients would fall into the "high healthcare utilization" category. **Materials and Methods.** A series of machine learning models were trained on a dataset extracted from a prospective natural history registry from a tertiary IBD center and associated healthcare charges. The models were trained to predict which patients are likely to have the highest healthcare utilization charges (top 15%). **Results.** A gradient-boosted trees classification model (accuracy 0.898, AUC 0.748) performed best out of the 12 evaluated modeling approaches. **Conclusion.** Classification models such as the ones evaluated in this work provide a reasonable basis for a clinical decision support system designed to predict which IBD patients are likely to become high expenditure.

1 INTRODUCTION


Inflammatory Bowel Disorders (IBD) is a group of gastric disorders that include well-known maladies such as Crohn's Disease and Ulcerative Colitis (UC), as well as a number of other gastric disorders that are not well classified. According to the Center for Disease Control (CDC), "IBD is one of the five most prevalent gastrointestinal disease burdens in the United States, with an overall healthcare cost of more than \$1.7 billion". Currently, there is no medical cure and IBD patients commonly require a lifetime of care. In the United States, IBD accounts for more than 700,000 physician visits, 100,000 hospitalizations, and disability in 119,000 patients (CDC 2014).


IBD patients most often receive care in physicians' offices or other outpatient sites, with hospitalization required only for severe disease presentation, to treat certain complications, and for surgery.

In recent decades the prevalence of IBD and the associated treatment costs have risen dramatically (Kappelman et al., 2008; Molodecky et al., 2012; Kappelman et al., 2013). In 2004, there were 1.1 million ambulatory care visits and 1.8 million prescriptions written for medications to treat Crohn's disease and 716,000 ambulatory care visits and 2.1 million prescriptions written for medications to treat UC (Everhart, 2008).

The hospitalization rate also increased significantly during this period from 44.2 to 59.7 per 100,000 population, with the mean hospitalization costs of \$11,345 for Crohn's disease and \$13,412 for ulcerative colitis (Kappelman et al., 2008; Molodecky et al., 2012; Kappelman et al., 2013).

A number of research efforts have produced machine learning (ML) models to predict remission in Crohn's patients (Waljee et al., 2019), patients' response to drug therapies (Waljee et al., 2010), and assess IBD risk (Wei et al., 2013). Other studies relied on classical statistical approaches to identify that a subgroup of IBD patients exhibit "high preva-

^a <https://orcid.org/0000-0003-1187-6684>

^b <https://orcid.org/0000-0001-6514-912X>

lence of depression, anxiety, and chronic pain” and that these comorbidities are ultimately responsible for high healthcare-related expenditures (Click et al., 2016; Mikocka-Walus et al., 2008; Filipovic and Filipovic, 2014).

However, to the best of our knowledge, no work has been done in creating ML models that classify IBD patients as high or low healthcare utilizers, nor has there been work in leveraging ML methods to identify best predictors of high healthcare utilization in IBD patients.

In developing ML models described in this paper, we explored 2019 and 2020 work of Morid, et. al. on healthcare cost prediction (Morid et al., 2019; Morid et al., 2020), as well as Morid, et. al. 2017 literature review of supervised ML methods for predicting healthcare costs (Morid et al., 2017). We attempted to replicate the Morid, et. al.’s work on predicting patients’ healthcare utilization from patient multivariate time series data using convolutional neural networks (CNN) (Morid et al., 2020), long short-term memory neural networks (LSTM), and gated recurrent units neural networks (GRU), but due to the idiosyncrasies of our data and due to a high number of missing values (described in subsection 2.2.3), we were unable to reach the level of model performance described by the authors.

The purpose of the work presented in this paper is to develop classification ML models that would aid in rapid identification of patients who are likely to become healthcare super-utilizers (Emeche, 2015) and to allow healthcare providers to offer focused treatment to these patients to ultimately reduce financial burden.

2 MATERIALS AND METHODS

2.1 The Data

The data used in this study was obtained from a natural history research registry of prospectively recruited IBD patients at a tertiary care center. At the time of this study, the registry contained demographic and clinical information for 3143 adult patients (age > 18) who were seen in the outpatient setting between 2009 and 2017 (Anderson et al., 2016). In order to ensure that all patients’ treatment trajectories contained longitudinal data, this study only included patients that had data for three or more years of continuous care within the University of Pittsburgh Medical Center (UPMC) hospital system. The final dataset used in this study contained 2915 patient records. The use of this data was approved by the Univer-

sity of Pittsburgh Institutional Review Board (IRB): STUDY19070426: Utilizing clinical metadata to predict high-cost complications and treatment response in IBD: development of clinical decision support tools STUDY19060285: UPMC Center for Inflammatory Bowel Disease (IBD) Research Registry

2.2 Feature Selection and Pre-processing

In our initial modeling efforts we relied on demographic and clinical predictors of high healthcare utilization in IBD patients identified and described by Click, et. al. in their 2016 work (Click et al., 2016).” More specifically, such predictors as gender, marital status, employment status, age, distance traveled to an IBD care center, medications prescribed, laboratory test results, clinical encounters, and psychiatric comorbidities were considered for all classification models.

2.2.1 Demographic And Social History Predictors

Gender. Even though previous studies did not identify gender as a predictor of high healthcare utilization and while IBD affects men and women equally, most North American studies show that UC is more common in men than in women. In addition, men are more likely than women to be diagnosed with UC in their 50’s and 60’s (Loftus et al., 2007). Given these considerations, gender was included as a feature in all the models described in this paper.

Marital status. The original marital status values from the registry dataset contained labels for “married”, “single”, “divorced”, “widowed”, “unknown”, “legally separated”, and “significant other”. Our initial modeling efforts indicated that, for example, “single”, “divorced”, “widowed”, and “legally separated” labels all had the same effect on each model’s output. To simplify model training and to reduce noise in the data, the original marital status categories were combined into “married”, “single”, and “unknown”.

Employment status. Similarly to the marital status feature, the original employment status categories were combined into “employed”, “not employed”, “student”, “unknown”.

Age. Patient’s age during the last year of recorded treatment

Proximity (distance) to IBD care center. Distance between each patient’s home address zip code and a corresponding IBD care center’s zip code was calculated using an open-source Python *zipcode* distance calculator (Hulett, 2013).

Tobacco Use. “Yes” if a patient indicated tobacco use at any time during the treatment period, otherwise “No”.

2.2.2 Clinical Predictors

Prescription drugs. The following categories of prescription drugs were selected for the dataset: (1) 5 ASA, (2) antibiotics, (3) anti-IL 12, (4) anti-Integrin, (5) anti-TNF, immunomodulators, (6) systemic steroids. The prescription data was represented in terms of the annual average consumption of each class of drugs (average number of times a drug was prescribed), and the duration of consumption in years.

Laboratory Test Results. The following categories of laboratory test results were selected for the dataset: (1) eosinophils (EOS) (Click et al., 2017), (2) monocytes (Cherfane et al., 2016), (3) albumin (Koutroubakis et al., 2015b), (4) hemoglobin (Koutroubakis et al., 2016), (5) erythrocyte sedimentation rate (ESR), (6) c-reactive Protein (CRP), and (7) vitamin D (Kabbani et al., 2016) were selected for the model’s features. For each laboratory test, three values were generated - a mean value, a minimum value, and a maximum value over the treatment period of interest.

Clinical Encounters. The following categories of clinical encounters were selected for the dataset:

- The number of office visits
- The number of outpatient procedures
- The number of telephone + email encounters
- The number of emergency department (ED) visits
- The number of hospitalizations.

Each clinical encounter category was represented with each patient’s average number of annual encounters (Ramos-Rivers et al., 2014).

Psychiatric Comorbidities. Psychiatric comorbidities were identified using ICD-10 codes F00 - F99 for mental, behavioral and neurodevelopmental disorders (icd, 2019), excluding code F17 (nicotine dependence) (nic, 2019). Psychiatric comorbidities were represented as a binary value - one (1) for presence and zero (0) for absence of psychiatric comorbidities.

Average Annual Charges. In addition to demographic and clinical data, financial charges data for both inpatient and outpatient healthcare service charges were obtained for each patient. The charges were inflated (in US dollars) to their 2018 equivalent using Consumer Price Index adjustment rates calculator¹. The charges related to non-IBD-related treatments, such as non-IBD-related surgeries (e.g. knee

replacement) or cancer treatments, were excluded from total charges calculations. As the primary purpose of the models described in this paper was to identify patients with the top 15% of the highest treatment charges (Click et al., 2016; Mandala Rayabandla, 2020), for the discrete dataset charges higher than the 85th percentile ($\geq \$47,644$) were categorized as “high”, otherwise as “normal” (Bhagya Rao et al., 2016).

2.2.3 Missing Values

Some of the laboratory test results features were missing as many as 30% of their values. To impute the missing data points, we compared three data imputation approaches - Multiple Imputation by Chained Equations (MICE) with Random Forest (Shah et al., 2014), Bayesian Ridge Regression multivariate feature imputation (BRRMFI), and Random Forest multivariate feature imputation (RFMFI). MICE imputation was implemented using the *miceforest* open-source Python package. Both BRRMFI and RFMFI were implemented using the *sklearn IterativeImputer* experimental feature. We specifically selected Bayesian Ridge (BR) instead of other possible linear regressors because Bayesian regression tends to perform better in situations where the data is either insufficient or poorly distributed; instead of estimating a single value for a missing value, BR draws it from a probability distribution.

For all three imputation techniques, we executed 10 iterations for each imputation (Raghunathan et al., 2002). In order to select the best-performing imputation approach, we used a subset of the data with no missing values. We generated missing values by randomly removing 30% of values from each laboratory test result feature. After imputing the values with all three techniques, we compared imputed values with the original values (Table 1). As RFMFI outperformed the other two imputation techniques, we used RFMFI for imputing missing values in the master dataset.

Table 1: Comparison of imputation accuracy between MICE, BRRMFI, and RFMFI.

Imputation Technique	Accuracy	RMSE
MICE	57.3%	0.71
BRRMFI	59.7%	0.59
RFMFI	68.5%	0.37

¹Consumer Price Index Inflation Calculator: https://www.bls.gov/data/inflation_calculator.htm

2.2.4 Label Encoding and Feature Scaling for Categorical Variables

All categorical variables such as gender, marital status, employment status, tobacco use, and psychiatric comorbidities were converted to numerical values using Python *sklearn* library’s *LabelEncoder* function. To avoid biased weight distribution of variables while training classification models, all categorical variables were scaled between the range of 0 and 1 using the *sklearn* library’s *MinMaxScaler* function.

2.2.5 Generated Datasets

The dataset described in previous sections (master dataset) has different numbers of years of continuous treatment for different patients, ranging from three years to 8 years per given patient. In other words, patients who have been treated longer have more data, and we were concerned that this would create bias in models’ predictions. To better understand how the “uneven” number of years of treatments would affect the models, two more datasets were generated for comparison. The first of these datasets was based on the aggregate data from the first three continuous years of each patient’s treatment (three-year static dataset). The second dataset used a rolling three-year window to predict outcomes in the fourth year. In other words, the predictors were aggregated from the first three years of each patient’s data, and the outcome (the response variable) was from the fourth year (Figure 1).

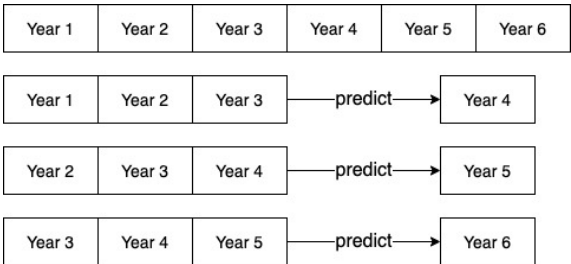


Figure 1: Illustration of generating a three-year rolling window dataset where aggregate data from three continuous years of treatment is used to predict outcomes in the fourth year of treatment.

2.3 Machine Learning Models

A total of twelve ML models were trained and validated, with four models trained and validated using each of the three datasets described in Section 2.2 (Feature Selection and Preprocessing). These models were trained using Random Forest (RF), Support

Vector Machine (SVM) with a linear kernel, Gradient Boosted Trees (GBT) (Lim et al., 2000; King et al., 1995), and a feedforward artificial neural network (ANN).

Random Forest (RF), SVM, and GBT models were trained using the scikit-learn machine learning library in Python. The ANN was trained using the TensorFlow Keras framework’s Sequential class and cross-validated using the scikit-learn library. All models’ hyperparameters were tuned using grid search - the hyperparameters used in the final models are shown in Table‘??’.

Table 2: Hyperparameters used to train the RandomForest, SVM, and GBT models.

Model	Parameter	Value
Random Forest	bootstrap	True
	max_depth	60
	max_features	3
	min_samples_leaf	5
	min_samples_split	10
	n_estimators	100
SVM	C	10
	gamma	0.001
	kernel	rbf
GBT	colsample_bytree	0.8
	max_depth	20
	n_estimators	400
	reg_alpha	1.3
	reg_lambda	1.5
	subsample	0.8
ANN	Number of layers	three
	Epochs	32
	Batch size	64
	Activation model	1:relu, 2:relu, 3:sigmoid
	Loss function	binary_crossentropy
	Optimizer	adam
	Test size	0.33

All models were trained to predict if a patient’s average annual charge is higher or lower than \$47644.00 (85th percentile).

All models were validated using 10-fold cross-validation; cross-validated accuracy scores and AUC (area under receiver operating characteristic curve (ROC) curve) were used as metrics to identify and select best-performing classification models.

Table 3: Models’ 10-fold Cross-Validated Accuracy and AUC Scores

	Master Dataset		Three-Year Static Dataset		Three-Year Rolling Window Dataset	
Algorithm	Accuracy	AUC	Accuracy	AUC	Accuracy	AUC
Random Forest	0.876	0.733	0.823	0.741	0.729	0.689
Support Vector Machine (SVM)	0.867	0.671	0.799	0.602	0.626	0.591
Gradient-Boosted Trees (GBT)	0.891	0.748	0.847	0.724	0.732	0.699
Feedforward ANN	0.927	0.782	0.729	0.631	0.613	0.526

3 RESULTS

3.1 Classification Models’ Accuracy

When trained on the largest (master) dataset, the ANN model outperformed all other models in terms of accuracy and AUC, with the GBT model coming in close second. However, as the size of the training data decreased in the static three-year dataset and decreased even further in the three-year rolling window dataset, the ANN’s accuracy and AUC dropped in comparison with the respective GBT models.

3.2 Feature Importance Ranking

Feature importance rankings were obtained using the “feature importance ranking feature” of the GBT XGBoost algorithm from 10-fold cross-validation of the GBT model. Table 4 shows importance rankings generated by the XGBoost algorithm for each of the GBT models trained on each of the datasets.

The average feature importance obtained over all the estimators in the model corresponds to previously published literature in clinical IBD research (Click et al., 2016; Ramos-Rivers et al., 2014; Click et al., 2015; Hashash et al., 2015; Koutroubakis et al., 2015a). The predictions are heavily reliant on the laboratory test results and clinical encounters. Certain demographic and social factors such as employment status and tobacco use are also discriminant in predicted patient charge. It is worth noting that as the size of the training data decreased in the static three-year and in the three-year rolling window datasets, corresponding GBT models relied more on clinical encounters rather than on laboratory test results.

4 LIMITATIONS

In discussing this work, it is important to acknowledge its limitations. One of the most critical limitations of constructing classification models on aggregate clinical data is that they do not take into account

the temporal nature of patient treatment trajectories. The models presented in this work are trained on data consisting of averaged values over patients’ entire history or over the course of three years of treatment, without consideration of how a patient’s state at a given time slice might affect that patient’s state in the future.

It is also important to note that IBD is an umbrella term that covers Ulcerative Colitis (UC) and Crohn’s disease. The datasets that we used for training ML models did not differentiate between UC and Crohn’s patients. When we attempted to separate UC and Crohn’s patients into different datasets, models trained on these subsets of the data performed poorly compared to models trained on the larger parent dataset (Table 5).

Last, but not least, large amounts of missing data presented another critical challenge. Some features of the dataset were missing as many as 30% of their values and imputation techniques used in creation of the models described in this paper could have inadvertently introduced bias.

5 DISCUSSION AND FUTURE WORK

Assessing and building predictive models for IBD using demographic clinical data is important given the recent rise in IBD’s prevalence in the United States. The GBT models described in this paper performed comparably to or better than machine learning classification models created in similar studies for other (non-IBD) disease states (Meng et al., 2013; Perveen et al., 2016; Sundar et al., 2012). The models’ cross-validated classification accuracy makes them reasonable candidates for clinical decision support systems (DSS), where patient care providers can input (or select) parameters for a new patient and leverage the models’ classification results to make decisions regarding IBD treatment choices.

As of the time of this writing, we began to develop a web-based DSS. This system will allow clinicians

Table 4: Top 10 predictors from the continuous dataset, ranked in terms of importance by XGBoost

Rank	Master Dataset	Three-Year Static Dataset	Three-Year Rolling Window Dataset
1	Albumin	Telephone encounters	Hospitalizations
2	Hemoglobin	Hospitalizations	Telephone encounters
3	Office visits	Emergency Department visits	Emergency Department visits
4	Eosinophils	Albumin	Psychiatric comorbidities
5	Erythrocyte Sedimentation Rate	Eosinophils	Systemic steroids usage
6	Emergency Department visits	Erythrocyte Sedimentation Rate	Office visits
7	Hospitalizations	Hemoglobin	Hemoglobin
8	Telephone encounters	Office visits	Albumin
9	Psychiatric comorbidities	Psychiatric comorbidities	Erythrocyte Sedimentation Rate
10	Systemic steroids usage	Systemic steroids usage	Eosinophils

Table 5: Cross-validated accuracy scores for GBT models trained separately on sub-cohort data of UC and Crohn’s patients obtained from the master dataset

Subcohort	Accuracy Score	AUC
CD	0.683	0.704
UC	0.722	0.689

to select or input demographic and clinical parameters, or import those parameters directly from an electronic medical records system (EMR) via Fast Healthcare Interoperability Resources (FHIR) application programming interface (API). We also began working on addressing two shortcomings that are common to some classification models. The first shortcoming, described in the “Limitations” section, is that the models described in this paper were trained on aggregate clinical data and that they do not take into account the temporal nature of patient treatment trajectories. In order to address this shortcoming, we are exploring alternative modeling approaches, including representing treatment trajectories with multiple chained Bayesian Network (BN) models (Barclay et al., 2013), hidden Markov chains (Petersen et al., 2018), and interval temporal BNs (Zhang et al., 2013).

The second shortcoming of many classification models, such as the ones produced by deep learning algorithms, is that these models are essentially “black boxes”. They accept certain inputs and produce an output (a prediction) without explaining how they arrived at that prediction. We are working on combining models’ predictions with patient treatment trajectory visualizations [52]–[54] to provide both a prediction and a visual explanation of how demographic and clinical features contribute to a given classification.

ACKNOWLEDGMENTS

While we take full responsibility for this work, we would like to thank the faculty and staff in the Digestive Disorders Center at UPMC who made this research endeavor possible. We would also like to thank the generosity of all the patients who agreed to participate in the IBD research registry.

Funding: (1) Framework for Smart Electronic Health Record-Linked Predictive Models to Optimize Care for Complex Digestive Diseases. Principal Investigator: Michael A. Dunn, MD, FACP. Funding Agency: Department of Defense. Grant/Contract No.: W81XWH-11-2-0133. (2) Utilizing Clinical Metadata to Predict High-Cost Complications and Treatment Response in IBD: Development of Clinical Decision Support Tools. Principal Investigator: David Binion MD. Funding Agency: Department of Defense. Grant/Contract No.: W81XWH-17-1-0556

BN models used in this project were built using GeNIe Modeler and SMILE engine, a Bayesian modeling environment developed at the Decision Systems Laboratory, University of Pittsburgh, and available free of charge for academic use at <http://www.bayesfusion.com/>.

REFERENCES

- (2019). 2019 ICD-10-CM Codes F01-F99: Mental, Behavioral and Neurodevelopmental disorders.
- (2019). 2019 ICD-10-CM Codes F17*: Nicotine dependence.
- Anderson, A. J., Click, B., Ramos-Rivers, C., Babichenko, D., Koutroubakis, I. E., Hartman, D. J., Hashash, J. G., Schwartz, M., Swoger, J., Barrie, A. M., et al. (2016). Development of an inflammatory bowel disease re-

- search registry derived from observational electronic health record data for comprehensive clinical phenotyping. *Digestive diseases and sciences*, 61(11):3236–3245.
- Barclay, L. M., Hutton, J. L., and Smith, J. Q. (2013). Refining a bayesian network using a chain event graph. *International Journal of Approximate Reasoning*, 54(9):1300–1309.
- Bhagya Rao, B., Koutroubakis, I. E., Ramos Rivers, C., Colombel, J. F., Regueiro, M., Swoger, J., Schwartz, M., Baidoo, L., Hashash, J., Barrie, A., Dunn, M. A., and Binion, D. G. (2016). Delineation of Crohn’s Disease Trajectories Using Change in Lémann Index: A Natural History Study. *Journal of Clinical Gastroenterology*, 50(6):476–482.
- Cherfane, C., Anderson, A. J., Rivers, C. R., Schwartz, M., Barrie, A., Hashash, J. G., Regueiro, M., Dunn, M. A., Swoger, J., and Binion, D. G. (2016). 165 Is Monocytosis a Biomarker of Severity in Inflammatory Bowel Disease? Analysis of a 6 Year, Prospective Natural History Registry. *Gastroenterology*, 150(4):S42.
- Click, B., Anderson, A. M., Koutroubakis, I. E., Rivers, C. R., Babichenko, D., Machicado, J. D., Hartman, D. J., Hashash, J. G., Dunn, M. A., Schwartz, M., Swoger, J., Barrie, A., Wenzel, S. E., Regueiro, M., and Binion, D. G. (2017). Peripheral Eosinophilia in Patients With Inflammatory Bowel Disease Defines an Aggressive Disease Phenotype. *The American Journal of Gastroenterology*, 112(12):1849–1858.
- Click, B., Ramos Rivers, C., Koutroubakis, I. E., Babichenko, D., Anderson, A. M., Hashash, J. G., Dunn, M. A., Schwartz, M., Swoger, J., Baidoo, L., et al. (2016). Demographic and clinical predictors of high healthcare use in patients with inflammatory bowel disease. *Inflammatory bowel diseases*, 22(6):1442–1449.
- Click, B., Vargas, E. J., Anderson, A. M., Proksell, S., Koutroubakis, I. E., Ramos Rivers, C., Hashash, J. G., Regueiro, M., Watson, A., Dunn, M. A., Schwartz, M., Swoger, J., Baidoo, L., Barrie, A., and Binion, D. G. (2015). Silent Crohn’s Disease: Asymptomatic Patients with Elevated C-reactive Protein Are at Risk for Subsequent Hospitalization. *Inflammatory Bowel Diseases*, 21(10):2254–2261.
- Emeche, U. (2015). Is a Strategy Focused on Super-Utilizers Equal to the Task of Health Care System Transformation? Yes. *The Annals of Family Medicine*, 13(1):6–7.
- Everhart, J. E. (2008). The Burden of Digestive Diseases in the United States | NIDDK.
- Filipovic, B. R. and Filipovic, B. F. (2014). Psychiatric comorbidity in the treatment of patients with inflammatory bowel disease. *World journal of gastroenterology: WJG*, 20(13):3552.
- Hashash, J. G., Chintamaneni, P., Ramos Rivers, C. M., Koutroubakis, I. E., Regueiro, M. D., Baidoo, L., Swoger, J. M., Barrie, A., Schwartz, M., Dunn, M. A., and Binion, D. G. (2015). Patterns of Antibiotic Exposure and Clinical Disease Activity in Inflammatory Bowel Disease: A 4-year Prospective Study. *Inflammatory Bowel Diseases*, 21(11):2576–2582.
- Hulett, C. (2013). Calculate the distance between zipcodes by lat/long data: cmhulett/zipcode.distance. original-date: 2012-07-09T06:30:09Z.
- Kabbani, T. A., Koutroubakis, I. E., Schoen, R. E., Ramos-Rivers, C., Shah, N., Swoger, J., Regueiro, M., Barrie, A., Schwartz, M., Hashash, J. G., Baidoo, L., Dunn, M. A., and Binion, D. G. (2016). Association of Vitamin D Level With Clinical Status in Inflammatory Bowel Disease: A 5-Year Longitudinal Study. *The American Journal of Gastroenterology*, 111(5):712–719.
- Kappelman, M. D., Moore, K. R., Allen, J. K., and Cook, S. F. (2013). Recent trends in the prevalence of Crohn’s disease and ulcerative colitis in a commercially insured US population. *Digestive Diseases and Sciences*, 58(2):519–525.
- Kappelman, M. D., Rifas-Shiman, S. L., Porter, C. Q., Ollendorf, D. A., Sandler, R. S., Galanko, J. A., and Finkelstein, J. A. (2008). Direct health care costs of Crohn’s disease and ulcerative colitis in US children and adults. *Gastroenterology*, 135(6):1907–1913.
- King, R. D., Feng, C., and Sutherland, A. (1995). Statlog: comparison of classification algorithms on large real-world problems. *Applied Artificial Intelligence an International Journal*, 9(3):289–333.
- Koutroubakis, I. E., Ramos-Rivers, C., Regueiro, M., Koutroumpakis, E., Click, B., Schoen, R. E., Hashash, J. G., Schwartz, M., Swoger, J., Baidoo, L., Barrie, A., Dunn, M. A., and Binion, D. G. (2015a). Persistent or Recurrent Anemia Is Associated With Severe and Disabling Inflammatory Bowel Disease. *Clinical Gastroenterology and Hepatology: The Official Clinical Practice Journal of the American Gastroenterological Association*, 13(10):1760–1766.
- Koutroubakis, I. E., Ramos-Rivers, C., Regueiro, M., Koutroumpakis, E., Click, B., Schwartz, M., Swoger, J., Baidoo, L., Hashash, J. G., Barrie, A., and others (2016). Five-year period prevalence and characteristics of anemia in a large US inflammatory bowel disease cohort. *Journal of clinical gastroenterology*, 50(8):638.
- Koutroubakis, I. E., Regueiro, M., Schoen, R. E., Ramos-Rivers, C., Hashash, J. G., Schwartz, M., Swoger, J., Barrie, A., Baidoo, L., Dunn, M. A., and others (2015b). Multiyear patterns of serum inflammatory biomarkers and risk of colorectal neoplasia in patients with ulcerative colitis. *Inflammatory bowel diseases*, 22(1):100–105.
- Lim, T.-S., Loh, W.-Y., and Shih, Y.-S. (2000). A comparison of prediction accuracy, complexity, and training time of thirty-three old and new classification algorithms. *Machine learning*, 40(3):203–228.
- Loftus, C. G., Loftus, E. V., Harmsen, W. S., Zinsmeister, A. R., Tremaine, W. J., Melton, L. J., and Sandborn, W. J. (2007). Update on the incidence and prevalence of Crohn’s disease and ulcerative colitis in Olmsted County, Minnesota, 1940–2000. *Inflammatory Bowel Diseases*, 13(3):254–261.
- Mandala Rayabandla, S. (2020). A review of the characteristics of super-utilizers and evidence-based approaches to reduce healthcare utilization.

- Meng, X.-H., Huang, Y.-X., Rao, D.-P., Zhang, Q., and Liu, Q. (2013). Comparison of three data mining models for predicting diabetes or prediabetes by risk factors. *The Kaohsiung Journal of Medical Sciences*, 29(2):93–99.
- Mikocka-Walus, A., Turnbull, D. A., Andrews, J., Moulding, N., and Holtmann, G. (2008). The effect of functional gastrointestinal disorders on psychological comorbidity and quality of life in patients with inflammatory bowel disease. *Alimentary pharmacology & therapeutics*, 28(4):475–483.
- Molodecky, N. A., Soon, I. S., Rabi, D. M., Ghali, W. A., Ferris, M., Chernoff, G., Benchimol, E. I., Panaccione, R., Ghosh, S., Barkema, H. W., and Kaplan, G. G. (2012). Increasing incidence and prevalence of the inflammatory bowel diseases with time, based on systematic review. *Gastroenterology*, 142(1):46–54.e42; quiz e30.
- Morid, M. A., Kawamoto, K., Ault, T., Dorius, J., and Abdelrahman, S. (2017). Supervised learning methods for predicting healthcare costs: systematic literature review and empirical evaluation. In *AMIA Annual Symposium Proceedings*, volume 2017, page 1312. American Medical Informatics Association.
- Morid, M. A., Sheng, O. R. L., Kawamoto, K., and Abdelrahman, S. (2020). Learning hidden patterns from patient multivariate time series data using convolutional neural networks: A case study of healthcare cost prediction. *Journal of Biomedical Informatics*, 111:103565.
- Morid, M. A., Sheng, O. R. L., Kawamoto, K., Ault, T., Dorius, J., and Abdelrahman, S. (2019). Healthcare cost prediction: Leveraging fine-grain temporal patterns. *Journal of biomedical informatics*, 91:103113.
- Perveen, S., Shahbaz, M., Guergachi, A., and Keshavjee, K. (2016). Performance Analysis of Data Mining Classification Techniques to Predict Diabetes. *Procedia Computer Science*, 82:115–121.
- Petersen, B. K., Mayhew, M. B., Ogbuefi, K. O., Greene, J. D., Liu, V. X., and Ray, P. (2018). Modeling sepsis progression using hidden markov models. *arXiv preprint arXiv:1801.02736*.
- Raghunathan, T. E., Solenberger, P. W., and Van Hoewyk, J. (2002). IVEware: Imputation and variance estimation software. *Ann Arbor, MI: Survey Methodology Program, Survey Research Center, Institute for Social Research, University of Michigan*.
- Ramos-Rivers, C., Regueiro, M., Vargas, E. J., Szigethy, E., Schoen, R. E., Dunn, M., Watson, A. R., Schwartz, M., Swoger, J., Baidoo, L., Barrie, A., Dudekula, A., Youk, A. O., and Binion, D. G. (2014). Association between telephone activity and features of patients with inflammatory bowel disease. *Clinical Gastroenterology and Hepatology: The Official Clinical Practice Journal of the American Gastroenterological Association*, 12(6):986–994.e1.
- Shah, A. D., Bartlett, J. W., Carpenter, J., Nicholas, O., and Hemingway, H. (2014). Comparison of random forest and parametric imputation models for imputing missing data using mice: a caliber study. *American journal of epidemiology*, 179(6):764–774.
- Sundar, N. A., Latha, P. P., and Chandra, M. R. (2012). Performance analysis of classification data mining techniques over heart disease database. *International journal of engineering science & advanced technology*, 2(3):470–478.
- Waljee, A. K., Joyce, J. C., Wang, S., Saxena, A., Hart, M., Zhu, J., and Higgins, P. D. R. (2010). Algorithms Outperform Metabolite Tests in Predicting Response of Patients With Inflammatory Bowel Disease to Thiopurines. *Clinical Gastroenterology and Hepatology*, 8(2):143–150.
- Waljee, A. K., Wallace, B. I., Cohen-Mekelburg, S., Liu, Y., Liu, B., Sauder, K., Stidham, R. W., Zhu, J., and Higgins, P. D. R. (2019). Development and Validation of Machine Learning Models in Prediction of Remission in Patients With Moderate to Severe Crohn Disease. *JAMA Network Open*, 2(5):e193721–e193721.
- Wei, Z., Wang, W., Bradfield, J., Li, J., Cardinale, C., Frackelton, E., Kim, C., Mentch, F., Van Steen, K., Visscher, P., Baldassano, R., and Hakonarson, H. (2013). Large Sample Size, Wide Variant Spectrum, and Advanced Machine-Learning Technique Boost Risk Prediction for Inflammatory Bowel Disease. *The American Journal of Human Genetics*, 92(6):1008–1012.
- Zhang, Y., Zhang, Y., Swears, E., Larios, N., Wang, Z., and Ji, Q. (2013). Modeling temporal interactions with interval temporal bayesian networks for complex activity recognition. *IEEE transactions on pattern analysis and machine intelligence*, 35(10):2468–2483.