Change Matters: Medication Change Prediction with Recurrent Residual Networks

Chaoqi Yang\textsuperscript{1}, Cao Xiao\textsuperscript{2}, Lucas Glass\textsuperscript{2} and Jimeng Sun\textsuperscript{1,∗}

\textsuperscript{1}Department of Computer Science, University of Illinois Urbana Champaign
\textsuperscript{2}Analytics Center of Excellence, IQVIA
chaoqiy2@illinois.edu, cao.xiao@iqvia.com, Lucas.Glass@iqvia.com, jimeng@illinois.edu

Abstract

Deep learning is revolutionizing predictive healthcare, including recommending medications to patients with complex health conditions. Existing approaches focus on predicting all medications for the current visit, which often overlaps with medications from previous visits. A more clinically relevant task is to identify medication changes.

In this paper, we propose a new recurrent residual networks, named MICRON, for medication change prediction. MICRON takes the changes in patient health records as input and learns to update a hidden medication vector and the medication set recurrently with a reconstruction design. The medication vector is like the memory cell that encodes longitudinal information of medications. Unlike traditional methods that require the entire patient history for prediction, MICRON has a residual-based inference that allows for sequential updating based only on new patient features (e.g., new diagnoses in the recent visit), which is efficient.

We evaluated MICRON on real inpatient and outpatient datasets. MICRON achieves 3.5% and 7.8% relative improvements over the best baseline in F1 score, respectively. MICRON also requires fewer parameters, which significantly reduces the training time by 38.3s per epoch with 1.5× speed-up.

1 Introduction

Recently years, deep learning has demonstrated initial success in potentially assisting clinical decision-making [Almirall et al., 2012; Choi et al., 2017; Xiao et al., 2018; Mao et al., 2019]. Among others, the medication recommendation task has drawn lots of research interest [Wang et al., 2017; Wang et al., 2019; Shang et al., 2019a; Shang et al., 2019b; Zhang et al., 2017; Killian et al., 2019; Wang et al., 2018]. The common strategy of medication recommendation learns representations for medical entities (e.g., diagnoses, medications) from electronic health records, and use the learned representations to predict medications that fit the patient’s health condition while avoiding adverse drug interactions.

Many existing works focus on recommending the full set of medications in a visit [Zhang et al., 2017; Shang et al., 2019a; Shang et al., 2019b; Xiao et al., 2018], which can be quite redundant from previous visits. Because the medications often remain stable over time with large overlaps between consecutive visits. For example, we investigate the Jaccard coefficient over consecutive visits on MIMIC-III data [Johnson et al., 2016] (Fig. 1). Among patients with multiple visits, although most of them are diagnosed with different conditions during consecutive visits (mean Jaccard below 0.2), the sets of medications remain stable (mean Jaccard around 0.5).

However, such medication patterns were rarely explored and leveraged to augment medication recommendation tasks. Challenges mainly arise from (1) how to accurately characterize the changes of patient health condition for each time step, and (2) how to correctly identify the medication changes based on health changes.

To fill in the gap, we propose a new recurrent residual learning approach, named Medication Change pRedictiON (MICRON) to predict medication changes and simultaneously model longitudinal medical history. MICRON is enabled by the following technical contributions.

• Efficient representation of changing health conditions. MICRON uses a residual health representation to sequentially update changes in patient health conditions, which provides more efficient model inference than RNN-based alternatives.

• Explicit change set prediction: MICRON decomposes the medication change prediction task into predicting two sets: (1) the removal set that removes previous medicines that are no longer needed; and (2) the addition set that brings in new medicines for newly developed diseases. Two sets are modeled by a recurrently updated medication vector and addi-
tion and removal thresholds selected at the high-confidence region from validation ROC-curve and thus could provide reliable inclusion-exclusion criterion.

We evaluated MICRON against state-of-the-art models on two real-world patient datasets: one inpatient MIMIC-III data and one outpatient dataset. MICRON outperforms the best baseline GAMENet [Shang et al., 2019b] with 3.5% and 7.8% relative improvement in F1 measure, respectively. In addition, MICRON achieves 1.5× speed-up in training and inference compared with GAMENet.

2 Related Works

Rule-based models [Almirall et al., 2012; Chen et al., 2016] typically rely on human-designed clinical guidelines, which require huge efforts from clinicians. For example, [Lakkaraju and Rudin, 2017] optimizes a sequence of if-then-else rules, which maps the patient status into the prescription decision.

Instance-based methods extract patient features only from current visits. [Zhang et al., 2017] formulated the medication recommendation as a multi-instance multi-label (MIML) task and proposed a content-attention mechanism-based sequence-to-sequence model. [Wang et al., 2017] jointly embedded diseases, medicines, patients, and their corresponding relations into a shared space by the knowledge graph, which requires multiple external data sources.

Longitudinal approach [Wang et al., 2018; Wang et al., 2019; Xiao et al., 2018; Bhoi et al., 2020] is a popular approach that captures the sequential dependency in patient treatment history. [Choi et al., 2016; Bajor and Lasko, 2017] modeled the longitudinal patient history by RNNs for various clinical predictive tasks. [Shang et al., 2019b] and [Le et al., 2018] adopted memory-based networks with RNNs to handle the dependency among longitudinal medical codes.

Compared with existing works, MICRON is based on a new perspective that focuses on predicting the changes. This is more realistic since clinicians usually update patient prescriptions by only a small proportion for a patient’s new visit.

3 Method

3.1 Problem Formulation

Definition 1 (Patient EHR Records) Patient EHR records are usually represented by an ordered sequence of tuples. For a patient $j$, we denote his/her clinical documentaries as $X_j = [x_j^{(1)}, x_j^{(2)}, x_j^{(3)}, \ldots]$, where the $t_{th}$ entry, $x_j^{(t)}$, records the information of the $t_{th}$ visit, such as diagnoses, procedures, and prescription information. In the paper, $x_j^{(t)} = [d_j^{(t)}, p_j^{(t)}, M_j^{(t)}]$, where $d_j^{(t)} \in \{0, 1\}^{|D|}$ and $p_j^{(t)} \in \{0, 1\}^{|P|}$ are multi-hot diagnoses and procedure vectors, while $D$ and $P$ are the overall diagnosis and procedure sets. $M_j^{(t)} \subset M$ is the $t_{th}$ medication set and $M$ is a set for all possible medicines. We denote the visit-wise medication addition (new) and removal (old) sets as $N_{\text{target}}^{(t)}$, $O_{\text{target}}^{(t)} \subset M$, separately, which naturally follow the equality, $N_{\text{target}}^{(t)} = (M^{(t-1)} \cup N_{\text{target}}^{(t)}) \setminus O_{\text{target}}^{(t)}$.

Problem 1 (Medication Change Prediction) Medication change prediction aims at determining the medication addition set $N^{(t)}$ and the removal set $O^{(t)}$ at visit $t$, given last prescription, $M^{(t-1)}$ and patient health history $[d^{(1)}, \ldots, d^{(t)}]$ and $[p^{(1)}, \ldots, p^{(t)}]$. The model aims to minimize the gap between current estimation $\hat{M}^{(t)} = (M^{(t-1)} \cup N^{(t)}) \setminus O^{(t)}$ and real prescriptions $M^{(t)}$, and also control the incidence of DDIs as denoted by $A \in \{0, 1\}^{M|D|\times|M|}$, where $A_{ij} = 1$ implies that medicine $i$ and $j$ could interact.

3.2 MICRON Method

Overview As shown in Fig. 2, MICRON has three modules: (1) a patient representation module that embeds diagnosis and procedure codes into latent health representation; (2) a prescription reconstruction module (training phase), where MICRON trains on consecutive pairs of visits and learns residual medication representations under a new reconstruction design; (3) a medication updating module (inference phase) for model inference, where MICRON initializes with previous medication information. For each subsequent visit, MICRON only requires an update of patient health status and then will predict the changes in the existing medications.

The key difference between MICRON and existing medication recommendation models [Shang et al., 2019b; Choi et al., 2016] is that while these models learn global sequential patterns using RNNs, MICRON learns sequential information locally (by every two consecutive visits) and propagates them visit-by-visit to preserve the longitudinal patient information.

3.3 Patient Representation

Patient representation aims to learn a compact and indicative vector to represent a patient’s status. In a clinical visit, doctors will recommend medications based on diagnosis and procedure information. Our module also feeds on these two features. Since MICRON is proposed for generic patients, we leave the subscript notation in the following.

Diagnosis and Procedure Encoders. For the $t_{th}$ visit, the input features, $d^{(t)} \in \mathbb{R}^{|D|}$ and $p^{(t)} \in \mathbb{R}^{|P|}$, can be extracted from clinical documentary. $d^{(t)}$ is the multi-hot diagnosis vector, while $p^{(t)}$ is the procedure vector. Following the similar strategy in [Zhang et al., 2017; Shang et al., 2019b], we transform these two vectors into the embedding space using mapping matrices $E_d \in \mathbb{R}^{s \times |D|}$ and $E_p \in \mathbb{R}^{s \times |P|}$ ($s$ is the size of embedding space).

$$d^{(t)} = E_d d^{(t)} \quad \text{and} \quad p^{(t)} = E_p p^{(t)}.$$ (1)

During training, these two tables are shared among all visits and patients. The results, $d^{(t)}$ and $p^{(t)}$, are of the same dimension $\mathbb{R}^s$.

Patient Hidden Representation. To achieve one compact health representation, $d_c^{(t)}$ and $p_c^{(t)}$ are further concatenated and parametrized by a health representation network, $\text{NET}_{\text{health}}$.

$$h^{(t)} = \text{NET}_{\text{health}} \left( [d_c^{(t)} \parallel p_c^{(t)}] \right),$$ (2)
Figure 2: MICRON Framework. To represent a patient health condition, the model first feeds on diagnosis and procedure information and then generates a compact patient health representation by health representation network, an affine function. During training, the model uses a feed-forward network for prescription network and learns the residual representation under a novel reconstruction loss. In the inference, our model inputs the health update to the same prescription network and then generates addition/removal sets to update the current prescription.

which outputs an integrated health representation \( \hat{h}(t) \in \mathbb{R}^d \). In this paper, we use affine function (one layer neural network without activation) for NET\text{health}.

Unlike previous works [Shang et al., 2019b; Zhang et al., 2017], this paper does not use recurrent neural networks (RNN) to capture a patient’s health history. Starting from \( h(0) \), the model architecture differs in training and inference. Next, we elaborate on these two phases.

### 3.4 Training: Prescription Reconstruction Module

Our MICRON trains on two consecutive visits, e.g., the \((t-1)\)th and the \(t\)th visits. Given the health representations, i.e., \( h(t-1) \) and \( h(t) \), a straightforward way for recommending medications is to learn a mapping, i.e., a prescription network, \( \text{NET}\text{med} : \mathbb{R}^d \rightarrow \mathbb{R}^{|M|} \), from hidden embedding space to medication space for two visits, separately.

\[
\tilde{m}(t-1) = \text{NET}\text{med} (h(t-1)), \quad (3) \\
\tilde{m}(t) = \text{NET}\text{med} (h(t)). \quad (4)
\]

where \( \tilde{m}(t-1), \tilde{m}(t) \in \mathbb{R}^{|M|} \) are medication representations and each entry quantifies a real value for the corresponding medicine. In the paper, \( \text{NET}\text{med} \) is implemented as a fully connected neural network. To obtain the actual recommendations, a trivial way [Shang et al., 2019a; Shang et al., 2019b] is to apply a medication output layer, which consists of a \textit{Sigmoid} function \( \sigma(\cdot) \), followed by a predefined threshold \( \delta \), picking up medicines with larger activation value. However, in this paper, we hope to utilize and emphasize the dependency usage between \( h(t-1) \) and \( h(t) \) in the model.

**Residual Medication Representation.** Formally, the difference between \( h(t-1) \) and \( h(t) \), i.e., \( r(t) = h(t) - h(t-1) \), is denoted as residual health representation, which encodes the changes in clinical health measurements, indicating an update in patient’s health condition. Naturally, the health update \( r(t) \) will cause an update in the resulting medication representation \( u(t) \). Our motivation is that if \( \text{NET}\text{med} \) can map a complete health representation (e.g., \( h(t-1) \)) into a complete medication representation (e.g., \( \tilde{m}(t-1) \)), then a residual health representation should also be mapped into an update in the same representation space through \( \text{NET}\text{med} \). In other words, \( r(t) \) and \( u(t) \) shall also follow the same mapping function, \( \text{NET}\text{med} \),

\[
u(t) = \text{NET}\text{med} (r(t)). \quad (5)
\]

To learn Eqn. (3) and (4), we could use the medication combinations in the dataset as supervision, however, it is hard to formulate direct supervision for Eqn. (5). A simple idea is to model the addition and the removal medication sets separately (as we show in the experiment that separate modeling DualNN does not work well). Therefore, we consider reconstructing \( u(t) \) from \( \tilde{m}(t-1) \) and \( \tilde{m}(t) \) by both unsupervised and supervised regularization.

**Unsupervised Residual Reconstruction.** To model the medication changes, we design a reconstruction loss. For Eqn. (3), (4) and (5), the inputs follow a residual relation: \( h(t-1) + r(t) = h(t) \). Naturally, we also impose a similar relation in the medication output layer by introducing an unsupervised reconstruction loss \( \sigma(\cdot) \) is a \textit{Sigmoid} function,

\[
L_{r_{\text{rec}}} = \| \sigma(\tilde{m}(t-1) + u(t)) - \sigma(\tilde{m}(t)) \|_2, \quad (6)
\]

which is calculated with \( L_2 \) norm. This reconstruction loss enforces the reconstructed recommendations from \( \tilde{m}(t-1) \) and the residual \( u(t) \) to be close to the recommendations given by \( \tilde{m}(t) \). We show in the experiment that \( L_{r_{\text{rec}}} \) is essential for learning the residual.

**Supervised Multi-label Classification.** To jointly modeling
a low DDI output, we introduce three differentiable loss functions to improve \( \hat{m}^{(t-1)} \) and \( \hat{m}^{(t)} \), so as to achieve a better reconstruction \( u^{(t)} \).

- **Drug-Drug Interaction Loss.** Since adverse drug-drug interaction (DDI) is a leading cause of morbidity and mortality in clinical treatments [Percha and Altman, 2013], we penalize the presence of DDIs in the output medication representation, \( \hat{m}^{(t)} \). First, we transform it by Sigmoid function, \( \hat{o}^{(t)} = \sigma(\hat{m}^{(t)}) \), and then design the DDI loss as,

\[
L_{ddi}^{(t)} = \sum_{i=1}^{N} \sum_{j=1}^{N} A_{ij} \cdot \hat{o}_{i}^{(t)} \cdot \hat{o}_{j}^{(t)},
\]

(7)

where \( A \) is the binary DDI matrix, extracted externally [Tatonetti et al., 2012] and \( A_{ij} \) indicates that medicine \( i \) and \( j \) have interaction or not. The term \( A_{ij} \cdot \hat{o}_{i}^{(t)} \cdot \hat{o}_{j}^{(t)} \) is the interaction penalty for medicine \( i \) and \( j \), and \( \hat{o}_{i}^{(t)} \) is the \( i \)-th element of the vector. Since we care about the DDI rate in the reconstructed representation, this loss only applies to the current visit \( t \).

- **Binary Cross-entropy Loss.** In addition, we also extract real medication set as supervision. Assume a multi-hot vector \( m^{(t)} \in \{0,1\}^{|M|} \) is the vectorization of the target medication set \( M^{(t)} \). We adopt binary cross entropy (BCE) loss,

\[
L_{bce}^{(t)} = -\sum_{i=1}^{N} m_{i}^{(t)} \log(\hat{o}_{i}^{(t)}) + (1-m_{i}^{(t)}) \log(1-\hat{o}_{i}^{(t)}),
\]

(8)

where subscript \( i \) indicates each element of the vectors. For this loss function, we compute on both \( \hat{m}^{(t-1)} \) and \( \hat{m}^{(t)} \).

- **Multi-Label Margin Loss.** Then, we employ margin-based loss to enlarge the gap between the recommended medications and the unselected ones. Since \( \hat{o}_{i}^{(t)} \in (0,1) \), the margin is set 1 in our paper.

\[
L_{multi}^{(t)} = \sum_{i,j} m_{i}^{(t)} \cdot m_{j}^{(t)} \max(0,1 - (\hat{o}_{i}^{(t)} - \hat{o}_{j}^{(t)})) / |M|.
\]

(9)

We also consider to penalize both of the visits, i.e., calculating \( L_{multi}^{(t-1)} \) and \( L_{multi}^{(t)} \) using this loss.

These three losses use external supervision to optimize the prescription network, so that during inference, our MICRO\( N \) would predict medication changes more accurately.

**Overall Loss Function.** In the training process, we hope to find optimal values for embedding tables, \( E_{q} \) and \( E_{p} \), parameter matrices in \( \text{NET}_{health} \) and \( \text{NET}_{med} \). The loss functions are combined by weighted sum,

\[
L_{total}^{(t)} = \lambda_{1} L_{rec}^{(t)} + \lambda_{2} L_{ddi}^{(t)} + \lambda_{3} \left( \gamma L_{bce}^{(t)} + (1-\gamma) L_{bce}^{(t-1)} \right) \\
+ \lambda_{4} \left( \gamma L_{multi}^{(t)} + (1-\gamma) L_{multi}^{(t-1)} \right),
\]

(10)

where \( \lambda_{i}, i = 1,2,3,4 \), are different weights for four types of loss functions, and \( \gamma \) is introduced to balance two consecutive visits. During the training, one batch contains all visits of one patient, and the loss is back-propagated after each batch. In the paper, we treat the weights as hyperparameters. In Appendix, we also prototype a momentum-based method to select the weights automatically.

3.5 Inference: Medication Updating Module
To predict medication changes, it is essential to maintain a medication combination. We hope that for the subsequent visit, it would be enough to derive an update in the combination based on new diagnosis or procedure information. However, like Risperdal for treating schizophrenia and bipolar disorder, some medicines will not be prescribed based on only one or two visits, and it might need long-term clinical observation. We therefore also maintain a medication vector, where each element quantifies the cumulative effect of a medicine. After clinical visits, each element in the vector will increase or decrease based on the updates of patient health status. Essentially, the medication vector is like the memory cell in RNNs, which is refreshed visit-by-visit. Once it is above or below certain thresholds, the medicine will be added or removed from the current sets. More concretely, the medicine change prediction follows three steps.

**Step 1: Medication Vector Update.** Specifically, for the \( t_{th} \) visit of a patient, the medicine changes start from a medication vector, \( \hat{m}^{(t-1)} \in \mathbb{R}^{|M|} \), and a medication set, \( M^{(t-1)} \subset M \). The model first updates the vector based on a residual health representation, \( r^{(t)} \),

\[
\hat{m}^{(t)} = \hat{m}^{(t-1)} + u^{(t)}
\]

(11)

where \( r^{(t)} \) is calculated by \( h^{(t)} - h^{(t-1)} \) (defined in Eqn. (2), \( \text{NET}_{health} \)), which is implemented as an affine function. We use an efficient smart inference module to calculate \( r^{(t)} \), in case only the updates in medical codes (e.g., diagnosis and procedure) are accessible. We specify it in Appendix.

**Step 2: Addition and Removal.** Then, based on the updated medication vector, \( \hat{m}^{(t)} \in \mathbb{R}^{|M|} \), we identify which medicines are ready to add or remove. We design two thresholds \( \delta_{1} \) is for the addition set, while \( \delta_{2} \) is for the removal set, where \( 1 \geq \delta_{1} \geq \delta_{2} \geq 0 \) to control the size of changes. Specifically, we first apply a Sigmoid function \( \sigma(\cdot) \), and then the addition and removal set are generated by applying the thresholds \( \delta_{1} \) and \( \delta_{2} \) element-wise,

\[
\mathcal{N}^{(t)} = \{ i \mid \sigma(\hat{m}_{i}^{(t)}) \geq \delta_{1} \},
\]

(12)

\[
\mathcal{O}^{(t)} = \{ i \mid \sigma(\hat{m}_{i}^{(t)}) \leq \delta_{2} \},
\]

(13)

where \( \mathcal{N}^{(t)} (\mathcal{O}^{(t)}) \) is for addition (removal) set, and subscript \( i \) enumerates the index of \( \hat{m}^{(t)} \). Note that, \( \mathcal{N}^{(t)} \cap \mathcal{O}^{(t)} = \emptyset \). For two thresholds, if \( \delta_{1} = 1 \) and \( \delta_{2} = 0 \), then \( \mathcal{N}^{(t)} = \mathcal{O}^{(t)} = \emptyset \); in another case, \( \delta_{1} = \delta_{2} \), then “medication change prediction” becomes “full medication prediction”.

The thresholds \( \delta_{1} \) and \( \delta_{2} \) are selected based on the receiver operating characteristic (ROC) of each medicine. Specifically, we load the pre-trained MICRO\( N \) on the validation set. For each medicine, we collect cut-off thresholds of the ROC curve in descending order. \( \delta_{1} \) is the average of 5-percentile over all medications, while \( \delta_{2} \) is based on 95-percentile. Essentially, \( \delta_{1} \) will provide a low false negative (FN) rate, while \( \delta_{2} \) ensures a low false positive (FP) rate.

**Step 3: Medication Set Update.** Next, we apply the changes (addition and removal) in the existing medication set. The
generation of a new combination is given by set operations,
\[ \tilde{\mathcal{M}}^{(t)} = (\tilde{\mathcal{M}}^{(t-1)} \cup \mathcal{N}^{(t)}) \setminus \mathcal{O}^{(t)}, \]

where we use set union and subtraction operation. \( \mathcal{N}^{(t)} \) and \( \tilde{\mathcal{M}}^{(t-1)} \) could have overlaps, while \( \mathcal{O}^{(t)} \) could also contain medications that are not in \( \tilde{\mathcal{M}}^{(t-1)} \). The overlaps will not affect the final recommendation results due to set operations.

To sum up, the model begins with a medication vector, \( \tilde{\mathbf{m}}^{(t-1)} \), and a medication set, \( \tilde{\mathcal{M}}^{(t-1)} \), which are provided by the previous visit. During the current visit, MICRON uses the update of patient status as input and walks through the above three steps to finish one round of medication change, as well as to update \( \tilde{\mathbf{m}}^{(t)} \) and \( \tilde{\mathcal{M}}^{(t)} \) for the next visit.

4 Experiments
We evaluate MICRON against several baselines in both inpatient and outpatient datasets. We focus on answering the following questions:

- How does MICRON perform against the baselines in medication and change prediction?
- How does MICRON perform in model efficiency?
- How do different components in MICRON contribute to accurate recommendations?

4.1 Experimental Setup
Dataset. We consider a benchmark inpatient dataset: MIMIC-III [Johnson et al., 2016], and a private outpatient dataset: IQVIA PharMetrics Plus (see processed statistics in Table 1). Details of dataset descriptions, preprocessing, hyperparameter selections can be found in Appendix.

| Items                  | MIMIC-III | IQVIA |
|------------------------|-----------|-------|
| # of visits            | 14,960    | 30,794|
| # of patients          | 6,335     | 3,023 |
| # of diagnosis codes   | 1,958     | 1,744 |
| # of procedure codes   | 1,430     | 1,250 |
| # of medication codes  | 131       | 155   |

Baselines. We consider the following baselines (SimNN and DualNN are designed by ourselves).

- SimNN use the same patient representation \( \mathbf{h}^{(t)} \) as MICRON and then learns a simple 3-way classifier for each medicine (add, remove, and remain) with the cross-entropy loss.
- DualNN also starts from patient representation \( \mathbf{h}^{(t)} \) and then diverges to two different neural networks. The first one is for addition and the second for removal. Each neural network classifier uses the binary cross-entropy loss.
- LEAP [Zhang et al., 2017] is an instance-based approach that uses a sequence to sequence model with reinforcement aftermath fine-tuning. This method generates a list of medications based on the diagnoses in the same visit.
- RETAIN [Choi et al., 2016] is a longitudinal predictive model, which designs a specialized attention model over RNN. It learns the temporal dependencies between clinical visits and makes medication recommendations.

![Figure 3: Illustration of Err(add) Metric at the t-th Visit](image)

- GAMENet [Shang et al., 2019b] is also a longitudinal model, which uses RNN, memory network, and graph neural network. It predicts medications using historical prescriptions as reference.

Evaluation Strategy and Metrics. We use evaluation metrics such as DDI rate, Jaccard Similarity, F1-score similar to evaluate the overall recommended medications, as other related works [Shang et al., 2019b; Zhang et al., 2017]. Also, we design new error metrics to evaluate the accuracy of medication changes: \( \text{Err(add)} \) and \( \text{Err(remove)} \).

\( \text{Err(add)} \) computes the sum of false positive part and false negative part (white region in Fig. 3) between the predicted addition set \( \mathcal{N}^{(t)} \) and the target addition set \( \mathcal{N}^{(t)}_{\text{target}} \). The target addition set is calculated by

\[ \mathcal{N}^{(t)}_{\text{target}} = \mathcal{M}^{(t)} \setminus \tilde{\mathcal{M}}^{(t-1)}, \]

where \( \mathcal{M}^{(t)} \) is the target medication set in the \( t \)-th visit, and \( \tilde{\mathcal{M}}^{(t-1)} \) is the predicted medication set at the \( (t-1) \)-th visit. For a particular patient \( j \), this metric is calculated from the second visit, where the medication changes start,

\[ \text{Err(add)}_j = \frac{1}{V(j)} \sum_{t=2}^{V(j)} \left( |\mathcal{A}^{(t)}_{\text{target}} \setminus \mathcal{N}^{(t)}| + |\mathcal{N}^{(t)} \setminus \mathcal{A}^{(t)}_{\text{target}}| \right), \]

where \( \mathcal{A} \setminus B \) is the set subtraction, and \( V(j) \) means total number of visits of patient \( j \). Finally, we average over all patients and get \( \text{Err(add)} \). Similarly, we design \( \text{Err(remove)} \) to denote errors for removal. Also, we report model size and training/inference time.

Since the evaluation is on medication change prediction, we assume the earliest visit appeared in the window as the “first” visit of a patient \( j \), where we could extract the initial medication set, \( \tilde{\mathcal{M}}^{(1)}_j = \mathcal{M}^{(1)}_j \), and the initial medication vector, \( \tilde{\mathbf{m}}^{(1)}_j = \mathbf{m}^{(1)}_j \). For a fair comparison, the evaluation of all models starts from the “second” visit. The definition of other metrics can be found in Appendix.

4.2 Experimental Results
We conduct experimental comparison based on five different random seeds and show the mean metric values in Table 2. MICRON outperforms all baselines in both inpatient and outpatient settings, especially for Jaccard and F1 metrics. MICRON gives a relatively good DDI measure on two datasets; however, its performance is weaker than other baselines in terms of accuracy. Although SimNN, DualNN, and RETAIN are implemented from very different perspectives, the former two
Table 2: Performance Comparison (on MIMIC-III / IQVIA)

| Metrics | DDI | Jaccard | F1 | Err(add) | Err(remove) | Model Size | Train(epoch) / Test |
|---------|-----|---------|----|----------|------------|------------|-------------------|
| SmNN    | 0.0837 / 0.0152 | 0.4658 / 0.1920 | 0.6235 / 0.2383 | 6.856 / 2.906 | 7.329 / 1.679 | 1.5MB (375,009 params) | 27.53s / 6.67s |
| DualNN  | 0.0925 / 0.0186 | 0.4880 / 0.1120 | 0.6447 / 0.1783 | 6.261 / 3.406 | 7.987 / 2.579 | 1.3MB (325,702 params) | 27.90s / 5.76s |
| RETAIN  | 0.0932 / 0.0279 | 0.4796 / 0.3320 | 0.6389 / 0.4215 | 8.552 / 2.353 | 6.338 / 0.927 | 1.2MB (287,940 params) | 34.78s / 6.97s |
| LEAP    | 0.0980 / 0.0134 | 0.4331 / 0.1871 | 0.5953 / 0.2742 | 9.105 / 3.663 | 5.939 / 1.286 | 1.7MB (433,286 params) | 199.94s / 26.45s |
| GAMENet | 0.0928 / 0.0166 | 0.4980 / 0.2025 | 0.6549 / 0.3016 | 8.810 / 3.016 | 5.854 / 2.179 | 1.8MB (449,092 params) | 55.31s / 8.84s |

The result of MIMIC-III and DS2 are reported together and separated by ‘/’. The last two metrics, Model Size and Train(epoch)/Test, are based on MIMIC-III dataset. For the other five metrics, we select the best results in bold font and use underscore to select the best baseline. We also report the improvement Δ of our MICRON over the best baseline.

Table 3: Ablation Study for Different Model Components (on MIMIC-III)

| Metrics | DDI | Jaccard | F1 | Err(add) | Err(remove) |
|---------|-----|---------|----|----------|------------|
| MICRON w/o $L_{rec}$ | 0.0695 / 0.0143 | 0.5234 / 0.3634 | 0.6778 / 0.4544 | 6.090 / 2.088 | 5.853 / 1.213 |
| MICRON w/o $	ilde{m}^{(i)}$ | 0.0696 / 0.0004 | 0.4509 / 0.0046 | 0.6096 / 0.0368 | 8.496 / 1.401 | 6.463 / 1.468 |
| MICRON w/o $L_{mult}$ | 0.0780 / 0.0015 | 0.5020 / 0.0072 | 0.6590 / 0.0288 | 6.544 / 0.2172 | 5.509 / 0.0732 |
| MICRON w/o $L_{ddi}$ | 0.0931 / 0.0005 | 0.5248 / 0.0006 | 0.6793 / 0.0081 | 6.402 / 0.3020 | 5.897 / 0.0397 |
| MICRON w/o $\delta_1$, $\delta_2$ | 0.0628 / 0.0018 | 0.5074 / 0.0016 | 0.6635 / 0.0026 | 7.216 / 0.1335 | 5.084 / 0.2706 |
| MICRON | 0.0695 / 0.0004 | 0.5234 / 0.0008 | 0.6778 / 0.0007 | 6.090 / 0.0189 | 5.853 / 0.0219 |

For DDI, Err(add), Err(remove) metrics, the lower the better, while for Jaccard and F1 metrics, the higher the better.

are instance-based while the latter uses sequence modeling. They show neck-to-neck performance on MIMIC-III. For outpatient medication change prediction (on IQVIA), RETAIN shows strong performance while some recent state of the art baselines failed, such as GAMENet. We hypothesize that time spans between two visits can be much longer for outpatients, and thus the stored memory can be less trustworthy in GAMENet. By learning an effective residual representation, MICRON provides more accurate and safe medication recommendations for inpatient or outpatient settings. Also, MICRON requires much fewer parameters than the state-of-the-art approaches, which is more efficient.

Due to space limitation, the standard deviation results are reported in the Appendix. We also test the model’s stability and do a T-hypothesis testing of MICRON on each metric. As a summary, most of the p-values are less than 0.001 (mean p-value at 6.2e-5), except in two cases on IQVIA: the DDI rate compared to LEAP and the Err(remove) compared to RETAIN.

4.3 Ablation Study on Model Components

In this section, we verify the effectiveness of different components in MICRON. Specifically, we conduct ablation studies on MIMIC-III and test on the following variants:

- (i) MICRON w/o $L_{rec}$. We remove the unsupervised loss during training and solely trained on the supervised loss.
- (ii) MICRON w/o $\tilde{m}^{(i)}$. We do not maintain the medication vector, $\tilde{m}^{(i)}$, and only utilizes the update feature information, $r^{(i)}$, between two visits;
- (iii) MICRON w/o $L_{mult}$. We remove $L_{mult}$, and it will be less confident to use thresholds, $\delta_1$ and $\delta_2$;
- (iv) MICRON w/o $L_{ddi}$. We remove DDI loss, and the model probably would provide high-DDI combinations;
- (v) MICRON w/o $\delta_1, \delta_2$. We set $\delta_1 = \delta_2 = \delta$, which implies medications with score above or equal $\delta$ being added, and medications with score less than $\delta$ being removed. This is a common strategy used in previous works: $\delta = 0.5$ in [Shang et al., 2019b] and $\delta = 0.3$ in [Shang et al., 2019a] (this model requires ontology information, so it is not included as baseline). We use $\delta = 0.5$ for this model variant.

The comparison results with variances (after ±) are shown in Table 3. Overall, all other variations perform better than variant (i) and (ii), highlighting that the reconstruction design and the initial medication vector are essential in the model. Without medication vector $\tilde{m}^{(i)}$, the model cannot retain the longitudinal information, thus variant (ii) provides poor results.

We also notice that without DDI loss, variant (iv) outputs a significantly higher DDI rate, and MICRON shows slightly better results than model variant (iii) without $L_{mult}$. By integrating all components, MICRON achieves a more balanced and stable performance in all metrics.

5 Conclusion

This paper tackles the medication change prediction problem and proposes a recurrent residual learning model, named MICRON, for predicting medication changes. We compare our model with state of the art approaches and show its effectiveness and efficiency on inpatient MIMIC-III dataset and a proprietary outpatient IQVIA dataset.

Like previous medication recommendation works, this paper uses the existing prescriptions as a gold standard. The efficacy of the recommendation is evaluated by comparing it with the prescriptions given by the dataset, which might be a limitation. In the future, we will perform a clinical user study to evaluate our results further. Also, we would like to consider three practical extensions: (i) enhance the model by utilizing relations between medications, e.g., similarities; (ii) consider medicine dosages during recommendation; (iii) penalize different medications based on patient-specific conditions.
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A Momentum-based Loss (MBL) Functions
As stated in the main text, the weights for different loss, $\lambda_i, i = 1, 2, 3, 4$, are treated as hyperparameters. To automate the procedure of hyperparameter search, we design momentum-based weights, which are adjusted adaptively during the training process. This module is primarily proposed for automatic selection of four hyperparameters, not for performance improvement.

Momentum-based Weights. The key advantage of using momentum is to combine current exploration with historical information. For each training epoch, we maintain a mean value for each type of loss, $\bar{L}^{(k)}$, which is calculated over the first $k$ training samples $(i = 1, 2, 3, 4$ stand for rec, ddi, bee, multi parts, separately). We use $L^{(k)}_i$ to denote the actual loss at the $k_{th}$ training point, and the momentum-based weights, $\lambda^{(k)}_i$, are calculated by the relative difference from the mean,

$$\text{diff}^{(k)}_i = \frac{L^{(k)}_i - \bar{L}^{(k-1)}_i}{\bar{L}^{(k-1)}_i},$$

$$\lambda^{(k)}_i = \gamma \cdot \frac{\exp(\text{diff}^{(k)}_i)}{\sum \exp(\text{diff}^{(k)}_i)} + (1 - \gamma) \cdot \lambda^{(k-1)}_i,$$

where we use the same $\gamma$ (in Eqn. (10)) to balance the current exploration and historical inertia. Meanwhile, the momentum values are also updated by,

$$\bar{L}^{(k)}_i = \frac{L^{(k)}_i + (k - 1) \cdot \bar{L}^{(k-1)}_i}{k}.$$

The momentum weights are in the same spirit as the negative multi parts, separately. We use $\text{diff}^{(k)}_i$ to denote the actual loss at the $k_{th}$ training point, and the momentum-based weights, $\lambda^{(k)}_i$, are calculated by the relative difference from the mean,

$$\text{diff}^{(k)}_i = \frac{L^{(k)}_i - \bar{L}^{(k-1)}_i}{\bar{L}^{(k-1)}_i},$$

$$\lambda^{(k)}_i = \gamma \cdot \frac{\exp(\text{diff}^{(k)}_i)}{\sum \exp(\text{diff}^{(k)}_i)} + (1 - \gamma) \cdot \lambda^{(k-1)}_i,$$

where we use the same $\gamma$ (in Eqn. (10)) to balance the current exploration and historical inertia. Meanwhile, the momentum values are also updated by,

$$\bar{L}^{(k)}_i = \frac{L^{(k)}_i + (k - 1) \cdot \bar{L}^{(k-1)}_i}{k}.$$

The momentum weights would enable our model to automatically identify and focus on the under-optimized parts during the training process. This module is primarily provided to denote the actual loss $\bar{L}^{(k)}_i$ and the momentum-based weights, $\lambda^{(k)}_i$, are calculated by the relative difference from the mean,

$$\text{diff}^{(k)}_i = \frac{L^{(k)}_i - \bar{L}^{(k-1)}_i}{\bar{L}^{(k-1)}_i},$$

$$\lambda^{(k)}_i = \gamma \cdot \frac{\exp(\text{diff}^{(k)}_i)}{\sum \exp(\text{diff}^{(k)}_i)} + (1 - \gamma) \cdot \lambda^{(k-1)}_i,$$

where we use the same $\gamma$ (in Eqn. (10)) to balance the current exploration and historical inertia. Meanwhile, the momentum values are also updated by,

$$\bar{L}^{(k)}_i = \frac{L^{(k)}_i + (k - 1) \cdot \bar{L}^{(k-1)}_i}{k}.$$

However, we can trace the cause back to the very beginning if $\text{NET}_{\text{health}}$ is affine,

$$\text{NET}_{\text{health}}(x - y) = \text{NET}_{\text{health}}(x) - \text{NET}_{\text{health}}(y), \forall x, y$$

where Eqn. (18) could be written as

$$r^{(t)} = \text{NET}_{\text{health}} \left( [d^{(t)}_i - d^{(t-1)}_i \parallel p^{(t)}_i - p^{(t-1)}_i] \right)$$

$$= \text{NET}_{\text{health}} \left( [d^{(t)}_i - d^{(t-1)}_i \cdot E_d \parallel (p^{(t)}_i - p^{(t-1)}_i \cdot E_p)] \right).$$

In fact, this equation reveals the causality between the update in diagnosis and procedure measurements and the update in patient health representation. For example, a patient get extra X-ray scanning at this visit while other diagnosis and procedure measurements are the same as the last time. Then, the model input is barely the code of X-ray, and the input will hopefully stimulate some of the medicines while discourage others, based solely on the X-ray information.

Eqn. (19) is practically efficient, since the clinical update $d^{(t)}_i - d^{(t-1)}_i$ (or $p^{(t)}_i - p^{(t-1)}_i$) is much sparser than original diagnosis documentary $d^{(t-1)}_i$ and $d^{(t)}_i$ (or procedure documentary $p^{(t-1)}_i$ and $p^{(t)}_i$). Also, it only requires one-time computation of $\text{NET}_{\text{health}}$ for the residual health representation.

C Datasets and Hyperparameter Settings
Here are the details about two datasets used in the paper.

• (i) MIMIC-III [Johnson et al., 2016] is a benchmark inpatient dataset, which collects electronic ICU records of Beth Israel Deaconess Medical Center between 2001 and 2012. We utilize the diagnosis, procedure, medication data and filter out patients with only one visit, so many patients will have 2 and more visits (up to 29 visits) in this data. From the original files in MIMIC-III “DIAGNOSES_ICD.csv”, “PROCEDURES_ICD.csv” and “PRESCRIPTIONS.csv”, we extract diagnosis, procedure and medication code list, separately, then. These three files are then merged by the patient id and “HADM_ID”, which is also used as visit id. After the merging, diagnosis and procedure are ICD-9 coded.

• (ii) IQVIA PharMetrics Plus is a private outpatient dataset. Patients in this database is generally representative of the under 65 commercially insured population in the U.S., who receives treatment without being admitted to a hospital from 2015 to 2019. We keep visit records with at least 3 medications. In this dataset, patients usually have around 10 visits. Similar to Figure 1 in the main text, we provide a Jaccard coefficient distribution for IQVIA dataset in Figure 4. Again, we observe that medications have larger overlaps than diagnosis.

The experimental settings are largely adopted from GAMENet [Shang et al., 2019b] with minor adjustments. For both of the datasets, we extract the DDI information from Top-40 severity types from TWOSIDES [Tatonetti et al., 2012]. We use ATC-3 Level drug coding to process all medications, use ICD-9 codes for diagnosis and procedures.

Table 4: Ablation Study on Momentum-based Loss (for MIMIC-III / DS2)

| Metrics         | MICRON | MICRON with MBL |
|-----------------|--------|-----------------|
| DDI             | 0.0695 / 0.0143 | 0.0690 / 0.0147 |
| Jaccard         | 0.5224 / 0.3634 | 0.5252 / 0.3479 |
| F1              | 0.6778 / 0.4544 | 0.6807 / 0.4536 |
| Err(add)        | 6.090 / 2.088 | 6.255 / 2.115 |
| Err(remoce)     | 5.853 / 1.213 | 5.623 / 1.157 |

B Smart Inference
This module will potentially improve the efficiency and interpretation of our model. Our model can reflect when each medicine is added or dropped and why (based on the appearance or disappearance of what diagnoses or procedures). Typically, during the inference phase, $r^{(t)}$ is calculated by

$$r^{(t)} = h^{(t)} - h^{(t-1)}$$

$$= \text{NET}_{\text{health}} \left( [d^{(t)}_i \parallel p^{(t)}_i] \right) - \text{NET}_{\text{health}} \left( [d^{(t-1)}_i \parallel p^{(t-1)}_i] \right).$$

However, we can trace the cause back to the very beginning if $\text{NET}_{\text{health}}$ is affine.
in MIMIC-III, and for IQVIA, we use ICD-10-CM codes for diagnoses and CPT/HCPCS codes for procedures. In MIMIC, “visit” is identified by the field “HADM_ID” in raw data file. When running the experiments, we use multi-hot encodings for the diagnosis and procedure vectors.

Two datasets are randomly split into training, validation and test by 60% : 20% : 20%. For MIMIC-III, we set embedding size $s = 64$ for diagnosis and procedure tables, $E_d, E_p$. The health representation network, $\text{NET}_{\text{health}}$, is an affine transformation, we implement it as one linear layer without activation function. The prescription network, $\text{NET}_p$, is a two-layer feed-forward neural network with 256 hidden units. The hyperparameters, $\gamma = 0.75, \eta = 0.08$, are selected from validation set. We choose RMSprop as the optimizer with learning rate at $2e^{-4}$ and weight decay at $1e^{-5}$. For IQVIA, we set $s = 32$, choose a three-layer $\text{NET}_{\text{med}}$ with 128 hidden units, the hyperparameters $\gamma = 0.75, \eta = 0.03$, while the learning rate is $3e^{-4}$. For two datasets, the hyperparameters for the loss function are $\lambda_i = 0.25, i = 1, 2, 3, 4$.

The implementation for baseline methods can be referred to RETAIN$^1$, LEAP and GAMENet$^2$. For MIMIC-III dataset, the hyperparameters of the baselines are mainly selected by grid search.

- For RETAIN, We choose two 64-dim GRUs as the implementation of two-level RNN with dropout rate at 0.5 for the output embedding. RMSprop is used as the optimizer with learning rate at $5 \times 10^{-4}$ for RETAIN and other deep learning baselines.
- LEAP is also implemented by 64-dim GRU as the feature encoder. However, we choose dropout rate at 0.3 between two layers, as 0.3 works better than 0.5 in the validation set. Particularly, since LEAP are sequence-based models, we set 20 as the max drug combination size.
- For GAMENet, we use the same suit of hyperparameters reported from the original paper [Shang et al., 2019b]: expected DDI rate at 0.05, initial annealing temperature at 0.85, mixture weights $\pi = [0.9, 0.1]$ and also use 64-dim embedding tables and 64-dim GRU as RNN. We find the hyperparameter works well in validation set, so we keep it for test.

For IQVIA, the embedding size and hidden layers are reduced to 32-dim. In both of the datasets, we could only observe a window of patient’s visits, instead of a complete visit history. Since the evaluation is on medication change prediction, we assume the earliest visit appeared in the window as the “first” visit of a patient $j$, and the evaluation of all models starts from the “second” visit. All experiments are implemented by PyTorch 1.4.0 on a Ubuntu server with 64GB memory, 32 CPUs and two GTX 2080Ti GPU. The reported results are averaged over 5 independent experiments with different random seeds.

### D Details about Metrics

This section provides the definition of each metric used in the experiment section.

We already present the calculation of $\text{Err}(\text{add})$ in the main text, in this section, we show the calculation of $\text{Err}(\text{remove})$, DDI, Jaccard coefficient (Jaccard), F1-score (F1). All the metrics are calculated from the observed “second” visits.

$\text{Err}(\text{remove})$. The $\text{Err}(\text{remove})$ metrics for a particular patient $j$ is calculated by

\[
\text{Err}(\text{remove})_j = \frac{1}{V(j)} \sum_{t=2}^{V(j)} |O^{(t)}_{\text{target}, j} \setminus O^{(t)}_j| + |O^{(t)}_j \setminus O^{(t)}_{\text{target}, j}|
\]

where $O^{(t)}_{\text{target}, j}$ is the target removal set, $O^{(t)}_j$ is the predicted removal set, $A \setminus B$ is set minus operation, $V(j)$ means total number of visits of patient $j$. $|\cdot|$ is for set cardinality, $|O^{(t)}_{\text{target}, j} \setminus O^{(t)}_j|$ and $|O^{(t)}_j \setminus O^{(t)}_{\text{target}, j}|$ are false negative and false positive numbers in terms of removal for the $t_{th}$ visit. The final $\text{Err}(\text{remove})$ is calculated by taking the average of all patients.

**DDI rate.** This metric is used to reflect the safety of drug combinations. As is stated in the main text, $M^{(t)}_j$ is the target medication set and $\hat{M}^{(t)}_j$ is the estimated medication set for patient $j$ at the $t_{th}$ visit. The DDI rate for patient $j$ is calculated by

\[
\text{DDI}_j = \frac{\sum_{t=2}^{V(j)} \sum_{m,n \in \hat{M}^{(t)}_j} 1\{A_{mn} = 1\}}{\sum_{t=2}^{V(j)} \sum_{m,n \in M^{(t)}_j} 1},
\]

where $V(j)$ is the total number of visits of the $j$-th patient, $A$ is the DDI matrix and $1\{\cdot\}$ is an indicator function, which returns 1 when the expression in $\{\cdot\}$ is true, otherwise 0. The reported DDI rate is by taking average of all patients.

**Jaccard.** The Jaccard coefficient for patient $j$ is calculated by

\[
J_{\text{Jaccard}}_j = \frac{1}{V(j)} \sum_{t=2}^{V(j)} |\hat{M}^{(t)}_j \cap M^{(t)}_j| \quad \frac{|\hat{M}^{(t)}_j \cup M^{(t)}_j|}{},
\]

while the overall Jaccard coefficient of the test data is by taking further average over all patients. In the main text, we report only the overall Jaccard coefficient.

**F1.** The F1 score is calculated by the harmonic mean of precision and recall. For patient $j$ at the $t$-th visit, the Precision, Recall, F1 are calculated by

\[
\text{Precision}_j^{(t)} = \frac{|\hat{M}^{(t)}_j \cap M^{(t)}_j|}{|\hat{M}^{(t)}_j|},
\]

\[
\text{Recall}_j^{(t)} = \frac{|\hat{M}^{(t)}_j \cap M^{(t)}_j|}{|M^{(t)}_j|},
\]

\[
F_1^{(t)} = \frac{2 \times \text{Precision}_j^{(t)} \times \text{Recall}_j^{(t)}}{\text{Precision}_j^{(t)} + \text{Recall}_j^{(t)}}.
\]
\[
Recall^{(t)}_j = \frac{|\hat{M}^{(t)}_j \cap M_j^{(t)}|}{|M_j^{(t)}|}
\]

\[
F1^{(t)}_j = \frac{2}{\frac{1}{\text{Precision}^{(t)}_j} + \frac{1}{\text{Recall}^{(t)}_j}}
\]

The F1 score for one patient \( j \) is by taking the average over his visits,

\[
F1_j = \frac{1}{V(j)} \sum_{t=2}^{V(j)} F1^{(t)}_j,
\]

while the overall F1-score of the test data is by taking further average over all patients. In the main text, we report only the overall F1-score.

E Standard Deviation and \( p \)-value

We provide the standard deviation and \( p \)-value results for performance comparison in MIMIC-III (Table 5) and IQVIA (Table 6).
Table 5: Performance Comparison on MIMIC-III

| Metrics | DDI          | Jaccard      | F1            | Err(add)       | Err(remove)    |
|---------|--------------|--------------|---------------|----------------|---------------|
| SimNN   | 0.0837 ± 0.0005 (2.5518e-11) | 0.4658 ± 0.0004 (6.6613e-16) | 0.6235 ± 0.0004 (4.4408e-16) | 6.856 ± 0.0054 (9.3702e-14) | 7.329 ± 0.0123 (1.5543e-15) |
| DualNN  | 0.0925 ± 0.0006 (6.9011e-13)  | 0.4880 ± 0.0004 (8.0386e-14)  | 0.6447 ± 0.0004 (5.5733e-14)  | 6.261 ± 0.0119 (7.6331e-07)  | 7.987 ± 0.0112 (0.0)       |
| RETAIN  | 0.0932 ± 0.0016 (1.8352e-09)  | 0.4796 ± 0.0006 (2.9309e-14)  | 0.6389 ± 0.0005 (2.1316e-14)  | 8.552 ± 0.0396 (2.4424e-15)  | 6.338 ± 0.0369 (1.6950e-08) |
| LEAP    | 0.0880 ± 0.0028 (3.2323e-06)  | 0.4331 ± 0.0011 (4.4408e-16)  | 0.5953 ± 0.0001 (4.4408e-16)  | 9.105 ± 0.0356 (2.2048e-16)  | 5.939 ± 0.0335 (0.0124)    |
| GAMENet | 0.0928 ± 0.0007 (1.8409e-12)  | 0.4980 ± 0.0012 (2.4894e-10)  | 0.6549 ± 0.0011 (2.5575e-10)  | 8.810 ± 0.1021 (4.8889e-12)  | 5.854 ± 0.0450 (0.9780)    |

* p-values are at the parenthesis.

Table 6: Performance Comparison on IQVIA

| Metrics | DDI          | Jaccard      | F1            | Err(add)       | Err(remove)    |
|---------|--------------|--------------|---------------|----------------|---------------|
| SimNN   | 0.0152 ± 0.0002 (0.0054)  | 0.192 ± 0.0003 (0.0)  | 0.2383 ± 0.0005 (0.0)  | 2.906 ± 0.0031 (0.0)  | 1.679 ± 0.0056 (1.0043e-12) |
| DualNN  | 0.0156 ± 0.0003 (0.0015)  | 0.112 ± 0.0003 (0.0)  | 0.1783 ± 0.0003 (0.0)  | 3.406 ± 0.0069 (0.0)  | 2.579 ± 0.0051 (0.0)       |
| RETAIN  | 0.0279 ± 0.0008 (6.7339e-10) | 0.332 ± 0.0002 (1.5543e-15) | 0.4215 ± 0.0003 (4.4408e-16) | 2.353 ± 0.0229 (3.7266e-08) | 0.927 ± 0.0169 (better) |
| LEAP    | 0.0134 ± 0.0013 (better)  | 0.1871 ± 0.0007 (0.0)  | 0.2742 ± 0.0008 (0.0)  | 3.603 ± 0.0205 (2.2204e-16) | 1.286 ± 0.0153 (0.0005)    |
| GAMENet | 0.0166 ± 0.0003 (1.7006e-05) | 0.2025 ± 0.0008 (0.0)  | 0.3016 ± 0.0007 (0.0)  | 3.016 ± 0.0589 (8.6596e-10) | 2.179 ± 0.0205 (9.7255e-14) |

* p-values are at the parenthesis.

* In this dataset, for Err(remove) metric, RETAIN is better than our MICRON. For DDI, LEAP is better than our MICRON.