

Comparing Generative Pre-trained Transformer Models to Physicians for Assigning Causes of Death from Verbal Autopsy: A Case Study of 6939 Deaths in Sierra Leone from 2019-2022

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Abstract

Background: Verbal Autopsies (VAs) collect data on deaths and their causes outside of traditional hospital settings to provide more representative counts and Causes of Death (CODs) for reducing premature mortality. Current computer models for COD assignment in VAs perform similar to physicians at the population level, but poorly at the individual level, due to a focus on structured questionnaire data and neglecting free text from the open narratives. Recently, a Generative Pre-trained Transformer (GPT) model called ChatGPT-4 has demonstrated human-level performance on professional and academic exams using free

text input. ChatGPT-4 shows promise in mimicking physician behavior for assigning CODs, but to the best of our knowledge, has yet to be tested for assigning CODs using open narratives from VAs.

Methods: 6939 records collected from VA in Sierra Leone from 2019 to 2022 were used to compare four computer models, GPT-3.5, GPT-4, InterVA-5, and InSilicoVA, to physicians for assigning CODs at the population and individual level. Open narratives were used for Chat-3.5/GPT-4 input, while structured questionnaires were used for InterVA-5/InSilicoVA input. All COD assignments were grouped into general COD categories consisting of 19, 10, and 7 categories for the adult, child, and neonatal age groups. Cause Specific Mortality Fraction (CSMF) accuracy and Partial Corrected Concordance (PCCC) were used to compare models to physicians at the population and individual level respectively. Comparisons in CSMF and PCCC to physicians among models were evaluated for all records and by COD, age group, and age ranges.

Results: Based on PCCC, GPT-4 had the best performance overall (0.61), followed by GPT-3.5 (0.58), InSilicoVA (0.44), and InterVA-5 (0.43). GPT-4 also had the best performance for the adult (0.65), child (0.57), and neonatal (0.62) age groups, while performance decreased as adults aged (0.72-0.59) and increased as children and neonates aged (0.5-0.7). 7 of 19, 4 of 10, and 1 of 7 adult, child, and neonatal CODs respectively had models with ≥ 0.8 PCCC. For most CODs, GPT models had one of the highest performances with the exception of InSilicoVA for adult tuberculosis, child pneumonia and neonatal infections. At the population level, all models had CSMF accuracy between 0.7-0.79.

Conclusion: GPT and InSilicoVA models were comparable to physicians for some CODs, but require further evaluation on reliability and larger datasets.

Keywords: Cause of Death, Physician Coding, Verbal Autopsy, GPT

1 Background

In 2019, 41 million people die prematurely from noncommunicable diseases every year, accounting for 74% of all deaths globally [1]. Most of these deaths are preventable, but require adequate resource allocation, guided by evidence, to implement effective interventions and policies that target populations at risk [2]. Thus, reliable counts and diagnoses of deaths enable decision makers to identify populations at risk to save lives and reduce premature deaths worldwide [3–6]. However, most low-income countries do not have data on deaths or have registered less than half of the deaths in their country, with an even fewer 8% of these registered deaths having a Cause of Death (COD) recorded [7]. To fill this gap in death registrations, an alternative method known as Verbal Autopsy (VA) is used to collect data on deaths and determine their likely causes at scale [8–10], outside of traditional healthcare facilities where over half of deaths occur at home [11].

VA involves two major components: survey and COD assignment [12–14]. In the survey component, trained lay surveyors interview those familiar with the deceased (e.g. living spouse, children, family, friends) to gather information using standardized questionnaires and open narratives. In the COD assignment component, physicians

evaluate information available from the questionnaires and open narratives to assign probable CODs. Although VA surveys have been an effective alternative to collect mortality data at scale (e.g. less than \$3 USD per house in India [15, 16]), COD assignment has been criticized to be expensive and difficult to reproduce due to reliance on physician assignment [17–19]. As an alternative to physician assignment, computer models, such as InterVA [20] and InSilicoVA [17], have recently been studied to automatically assign CODs with performances close to physicians at the population level, but poor performances at the individual level [21–25]. These computer models often utilized data from the structured questionnaire, but often omit the free-text open narrative, which misses latent information, such as chronology or health-seeking behaviors, that may potentially help models perform better than using the questionnaire alone [26–28].

Recently, Large Language Models (LLM), leveraging massive datasets and deep learning approaches, have made advances in performing a variety of Natural Language Processing (NLP) tasks using free-text, such as question answering, code generation, and even medical diagnosis [29–32]. On November 30, 2022, a widely-available LLM called ChatGPT was released by OpenAI with capabilities of answering natural language text inquiries using training data up to September 2021. ChatGPT-3 was based on several Generative Pre-trained Transformer (GPT) models between 2018 to 2020, namely GPT-1 to GPT-3, which had notable differences in training data sizes of 5 gigabytes to 45 terabytes from web sources that resulted in 117 million to 175 billion parameter models [33]. On March 14, 2023, ChatGPT-4 was released with human-level performance on various professional and academic exams and benchmarks that outperformed ChatGPT-3 [?]. Given the limited usage of free-text open narratives in computer models for determining CODs, and recent advances in LLMs that leverage natural language text prompts, we conduct a case study with Sierra Leone deaths from VA in 2019 to 2022 to compare four models, GPT-3.5, GPT-4, InterVA-5, and InSilicoVA, to physicians for determining CODs.

2 Methods

This study uses 6939 physician agreed records of 11,920 records collected in 2019 to 2022 from the Healthy Sierra Leone (HEAL-SL) study as described in Section 2.1. Section 2.2 describes the four models, GPT-3.5, GPT-4, InterVA-5, and InSilicoVA, for COD assignment, and their inputs and outputs, while section 2.3 details the performance evaluation of the four models relative to physicians overall, by ages, and by COD, using population and individual level metrics. Figure A1 in Appendix A details the methods used in this study.

2.1 Verbal Autopsy (VA) Data

Initially, 11,920 records¹ from the HEAL-SL study [34, 35] were collected from dual-coded EVA, where each record was randomly coded by two different physicians that assigned CODs as International Classification of Diseases Revision 10 (ICD-10) codes [36]. Physicians were able to assign CODs for 11,820 of the 11,920 records, where 100

¹ Available at openmortality.org/dataset/heal-sl

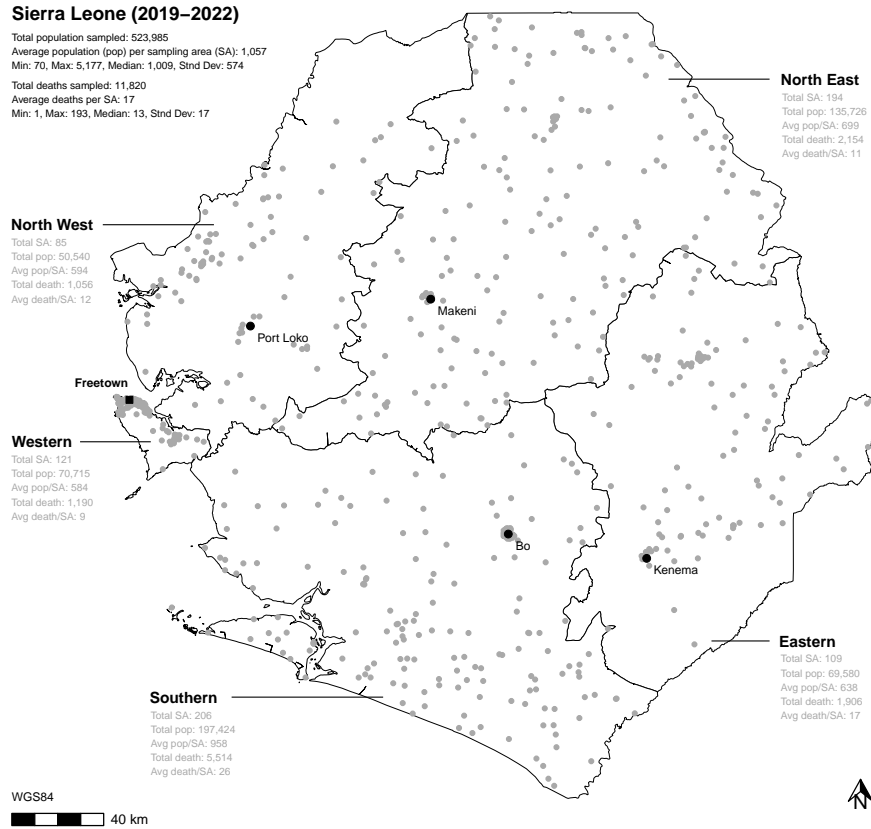


Fig. 1 Case study sample areas. VA records were collected from sample areas in Sierra Leone between 2019-2022 from the HEAL-SL study. Sample deaths shown represent records with physician assigned CODs only.

of these records could not be assigned a COD due to missing or inadequate information (e.g. low quality narrative, data loss). To determine if two codes were in physician agreement per record, codes were compared for similarity using Central Medical Evaluation Agreement 10 (CMEA-10) codes, which groups a range of similar ICD-10 codes together indicating codes in agreement [37] (see Additional File 2). When codes were not in agreement, a record enters the reconciliation phase, where the two physicians were provided reasoning and initial codes from each other to: (1) keep their initial code (2) assign the other physician's code or (3) assign a new code. If codes were not in agreement after the reconciliation phase, a record enters the adjudication phase, where a third senior physician evaluates both physicians' reasoning and codes before and after reconciliation, and assigns a final code based on their evaluation. The 11,820 physician coded records were further filtered for records where both physicians agreed on the assigned codes (records that were not reconciled or adjudicated) resulting in

6942 physician agreed records. Since computer models were compared to physicians in this study, there was more certainty that COD assignments agreed by both physicians were representative of physician assignment than when they disagreed [18, 38, 39]. The 6942 records were converted into CGHR-10 codes (see Additional File 1) that generalized ICD-10 codes into 19, 10, and 7 categories for the adult (12 to 69 years), child (28 days to 11 years), and neonatal (under 28 days) age groups. After conversion, a final total of 6939 physician agreed records (3826 adult, 2636 child, and 477 neonatal) were used for modelling and performance evaluation, where three records were removed as their ICD-10 codes did not have a matching CGHR-10 code.

The 6939 physician agreed records were relatively evenly distributed (approximately 40-57% male and female) for the adult, child, and neonatal age groups in terms of sex (Figure B2) with the most records in the 1-5 year (n=1633, 24%) age range, and the least records in the 10-14 year (n=135, 2%) and 7-27 day (n=82, 1%) age ranges (Figure B3). The other 15 five-year age ranges within 0 days to 69 years were relatively evenly distributed with approximately 4-6% of the 6939 records each. The 3826 adult records had most records in the 65-69 year (n=575, 15%), and the least in the 10-14 year (n=135, 4%) age ranges, while the other 10 age ranges were relatively evenly distributed at 7-9% of all records (Figure C4). For adult CODs, Malaria (n=799, 21%) had the highest number of adult records, and cancers (n=49, 1%), diabetes mellitus (n=27, <1%), and suicide (n=3, <1%) had the lowest number adult of adult records, while the other 15 CODs had between 2-11% of all adult records (Figure C5). The 2636 child records had most records in the 1-5 year (n=1633, 62%) age range while the three other age ranges were relatively evenly distributed at 12-14% of all records (Figure D6). For child CODs, Malaria (n=1382, 52%) and other infections (n=667, 25%) had the highest number of child records, while nutritional deficiencies (n=11, <1%) and congenital anomalies (n=1, <1%) had the lowest number of records with the five other CODs between 3-7% of all child records. The 477 neonatal records had two age ranges with most records in the 0-6 day (n=395, 83%) age range and the rest in the 7-27 day (n=82, 17%) age range (Figure E8). For neonatal CODs, stillbirth (n=172, 36%) had the highest number of neonatal records, and ill-defined (n=23, 5%), other (n=5, 1%), and congenital anomalies (n=2, <1%) had the least number of records with the rest of the other three CODs between 15-22% of all neonatal records (Figure E9). See Appendices B to E for a list of figures B2 to E9 showing distributions of the 6939 physician agreed records.

2.2 Modelling

Four computer models were used to assign COD for each of the 6939 physician agreed records: GPT-3.5, GPT-4, InterVA-5, and InSilicoVA. Each model required pre-processing of the 6939 records into input data, and standardization of output COD codes from models for performance evaluation as not all models produced comparable codes across outputs. Although each model can assign multiple CODs per record, only the first generated COD response from GPT-3.5 and GPT-4, and the most probable COD from InterVA-5 and InSilicoVA were used for evaluation. All model outputs were converted to CGHR-10 codes to evaluate performances of models for COD assignment relative to physicians.

2.2.1 Overview of GPT-3.5/4, InterVA-5, and InSilicoVA

GPT-3.5 [40] and GPT-4 [?] are LLMs that utilize deep neural networks with transformer architectures [41] and reinforcement learning from human feedback [42–45] to follow instructions from prompts and provide human-level responses, with known differences in GPT-4 possessing multimodal capabilities (e.g. image/voice input/output), more recent training data, and improved responses compared to ChatGPT-3 [33]. GPT-3.5 and GPT-4 were instructed with text prompts to assign CODs based on the open narrative. InterVA-5 and InSilicoVA are widely used and studied standard statistical models [13, 21, 22, 24, 25, 46, 47] for COD assignment in VAs under the openVA framework [48]. InterVA-5 applies Bayesian probabilistic modelling [49] using a set of standardized symptoms from reports and related conditional probabilities from medical experts to assign CODs based on the highest probability [20, 50]. InSilicoVA improves upon InterVA (e.g. comparable probabilities across individuals, measures of uncertainty, and inclusion of additional data sources) with a hierarchical Bayesian framework and Markov Chain Monte Carlo (MCMC) simulations [51–53] to incorporate multiple sources of uncertainty for assigning CODs based on the highest probability [17]. For assigning CODs, GPT-3.5 and GPT-4 require prompts containing conversation-like textual instructions as input, while InterVA-5 and InSilicoVA require structured symptom and associated sociodemographic data as input.

2.2.2 Input Data and Preprocessing

For GPT-3.5 and GPT-4, 6939 text prompts were generated for each physician agreed record as input to instruct the models to assign CODs based on the open narratives. Two types of text prompts were used: user prompts and system prompts. System prompts contained textual instructions to assign the role of a physician ICD-10 coder with expertise in Sierra Leone. The following system prompt was used for each record:

You are a physician with expertise in determining underlying causes of death in Sierra Leone by assigning the most probable ICD-10 code for each death using verbal autopsy narratives. Return only the ICD-10 code without description. E.g. A00. If there are multiple ICD-10 codes, show one code per line.

User prompts contained textual instructions to perform coding of VA records based on the age, sex, and narrative of the deceased. The following template was used to generate user prompts for each record, where <age> and <sex> from the questionnaire, and <narrative> from the narratives, were replaced with values from the data:

Determine the underlying cause of death and provide the most probable ICD-10 code for a verbal autopsy narrative of a <age> years old <sex> death in Sierra Leone: <narrative>

For InterVA-5 and InSilicoVA, the standardized questionnaire data from the HEAL-SL EVA were first converted into 2016 World Health Organization (WHO) VA questionnaire revision 1.5.1 Open Data Kit (ODK) format [54, 55] consisting of 526 variables [56], followed by further conversion into OpenVA format [48] consisting of 353 variables [57] using the pyCrossVA version 0.97 Python package [58]. The 6939 records were all converted into OpenVA formatted records for InterVA-5 and InSilicoVA.

2.2.3 Models and Parameters

The GPT-3.5 and GPT-4 Application Programming Interface (API) was accessed using Python version 3.11.4 and used to assign CODs for each record. GPT-3.5 used the `gpt-3.5-turbo` model, while GPT-4 used the `gpt-4-0613` model. The parameter `temperature` for GPT-3.5 and GPT-4, representing the sampling temperature ranging from 0 to 2 (default of 1), was set to 0 to produce more deterministic outputs [59]. Higher values closer to 2 may produce less deterministic outputs, while lower values closer to 0 produce more deterministic outputs.

The `openVA` R package was used to run InterVA-5 and InSilicoVA models to assign CODs for each record in R version 4.3.1. The `openVA` package version 1.1.1 used dependent packages `InterVA5` version 1.1.3 and `InSilicoVA` version 1.4.0. The `Nsim` (number of iterations to run) parameter [60] for InSilicoVA was set to 9500², while the `HIV` (level of prevalence of human immunodeficiency virus) and `Malaria` (level of prevalence of Malaria) parameters [61] for InterVA-5 were both set to 'h' (high) reflecting HIV and Malaria disease assumptions in Sierra Leone [62, 63].

2.2.4 Output Data and Code Conversions

Of the 6939 input records, GPT-3.5, GPT-4, InterVA-5, and InSilicoVA were able to assign CODs for 6939 (100%), 6935 (>99%), 6830 (98%), 6830 (98%) records respectively. All 6830 (100%) InterVA-5 and InSilicoVA records with WHO VA 2016 v1.5 output codes [64] were converted into ICD-10 codes respectively. After all model outputs were converted to ICD-10 codes, they were further converted to CGHR-10 codes. The 6939 GPT-3.5 and 6935 GPT-4 output records with ICD-10 codes were converted into 6930 (>99%) and 6931 (>99%) records with CGHR-10 codes, where <1% (9 and 8) records did not have matching CGHR-10 codes respectively. The 6830 InterVA-5 and InSilicoVA records with ICD-10 codes were converted into 6802 (>99%) and 6726 (98%) records with CGHR-10 codes respectively, where 28 (<1%) and 104 (1%) of records could not be converted into CGHR-10 codes.

2.3 Performance Evaluation

The performance of four models, GPT-3.5, GPT-4, InterVA-5, and InSilicoVA, were evaluated with metrics on the population and individual level by comparing their CGHR-10 COD outputs to 6939 records. Cause Specific Mortality Fraction (CSMF) accuracy was used to evaluate models on the population level, while Partial Chance Corrected Concordance (PCCC) was used to evaluate models on the individual level [65]. Records that were assigned a COD by physicians, but not by a model were considered to be an incorrect COD assignment by the model. CSMF accuracy and PCCC were calculated for each model by three age groups, and further into age ranges and COD for each age group.

²The default value of `Nsim`=10000 for InSilicoVA ran until 9500 iterations before it stopped due to errors, thus `Nsim`=9500 was used and ran successfully for all iterations.

2.3.1 Cause Specific Mortality Fraction (CSMF) Accuracy

CSMF accuracy measures the performance of models at the population level, comparing distributions of CODs between the physicians and the models [65]. To calculate CSMF accuracy, we first calculate $CSMF_j$ as is the fraction of physician or model records for cause j , given by dividing the number of records for cause j with the total number of records as seen in Equation 1. Then, the $CSMF_{MaximumError}$, representing the worst possible model, is calculated using Equation 2. Finally, the CSMF accuracy is given by Equation 3, where k is the number of causes, j is a cause, $CSMF_j^{true}$ is the true physician CSMF for cause j , and $CSMF_j^{pred}$ is the prediction model CSMF for cause j . CSMF accuracy ranges from 0 to 1, where 1 means that the model completely matched the physician COD distribution and 0 means that it did not match the distribution at all.

$$CSMF_j = Records_j / Records \quad (1)$$

$$CSMF_{MaximumError} = 2(1 - \min(CSMF_j^{true})) \quad (2)$$

$$CSMF_{Accuracy} = 1 - \frac{\sum_{j=1}^k |CSMF_j^{true} - CSMF_j^{pred}|}{CSMF_{MaximumError}} \quad (3)$$

2.3.2 Partial Chance Corrected Concordance (PCCC)

PCCC measures the performance of models at the individual level, comparing COD assignments between the physicians and models on a record by record basis, correcting for COD assignments made purely by chance [65]. PCCC is given by Equation 5, where k is the number of top COD assignments from the model to consider, N is number of causes, and C is fraction of records where the physician COD assignment is one of the top COD assignments from the model. For this study, we set k to 1, making C equivalent to the fraction of true positives TP or records where the physician COD assignment is equal to the model COD assignment as shown in Equation 4. Higher PCCC values closer to 1 indicate that model COD assignments are similar to physician COD assignments, while values closer to 0 indicate that model COD assignments are not similar to physicians.

$$C = \frac{TP}{Records} \quad (4)$$

$$PCCC(k) = \frac{C - \frac{k}{N}}{1 - \frac{k}{N}} \quad (5)$$

2.3.3 Metrics Overall and by Age and Cause of Death

The CSMF accuracy and PCCC metrics were calculated and compared for each model overall and by age group, followed by age ranges and COD for each age group as model performance can vary across ages and specific causes [46, 47, 66]. Metrics were calculated overall for three age groups according to the CGHR-10 codes: adult (12

to 69 years), child (28 days to 11 years), and neonatal (under 28 days). For each of the adult and child age groups, metrics were calculated for five-year age ranges for records with ages at death of one-year or older and five-month age ranges for 28 days or older. For the neonatal age group, the age ranges of 0-6 days and 7-27 days were used. Metrics were also calculated by CODs defined by CGHR-10 codes, which include 19, 10, and 7 CODs for adult, child, and neonatal records respectively.

3 Results

This section details the performance results of GPT-3.5, GPT-4, InterVA-5, and InSilicoVA models for assigning CGHR-10 CODs after applying the methods in Section 2. GPT-4 performed the best overall at 0.61 PCCC followed by GPT-3.5 at 0.58 PCCC. GPT-4 also had the highest PCCC for most age ranges and CODs across the adult (12 to 69 years), child (28 days to 11 years), and neonatal (under 28 days) age groups with GPT-3.5, InterVA-5, and InSilicoVA having higher PCCC values for a few age ranges and CODs. Overall performance results are seen in Section 3.1, and performance by adult, child, and neonatal records are seen in Sections 3.2, 3.3, and 3.4 respectively.

3.1 Overall Performance

Of the 6939 records, GPT-4 had the highest PCCC followed by GPT-3.5, InSilicoVA, and InterVA-5 at 0.61, 0.58, 0.44, and 0.43 PCCC respectively (Table 1). GPT-3.5 and GPT-4 had improvements ranging from 0.14-0.18 PCCC over InSilicoVA and InterVA-5, while GPT-4 slightly improved over GPT-3.5 by 0.03 PCCC. CSMF accuracies were above 0.7 for all models at 0.79, 0.74, 0.74, and 0.78 for GPT-4, GPT-3.5, InSilicoVA, and InterVA-5 respectively. Figure 2 shows the PCCC performance across age groups with reference to the CSMF Accuracy. GPT-4 had the highest PCCC at 0.65 and 0.62 for the adult and neonatal age groups, while GPT-3.5 had the highest PCCC at 0.57 for the child age group with GPT-4 performing slightly worse at 0.54. GPT-3.5 had the second highest PCCC at 0.56 for the adult age group, while InSilicoVA had the second highest PCCC for the neonatal age group at 0.56. InSilicoVA and InterVA-5 performed the worse for both adult and child age groups at PCCC scores below 0.5, while GPT-3.5 performed the worse for the neonatal age group with a PCCC of 0.42. The PCCC for models had larger differences between the minimum and maximum PCCC for the adult age group at 0.24, than the child and neonatal age groups at 0.12 and 0.20 respectively. For reference, all records, including non-physician agreed records, were also coded by GPT-3.5, GPT-4, InterVA-5, and InSilicoVA for comparison to physician agreed records. For physician agreed records, models had 0.05 to 0.09 higher PCCC values and 0.01 to 0.05 higher CSMF accuracy values than for all records (see Figure F10 in Appendix F).

Table 1 Overall model performance for physician agreed records (n=6939)

Model	PCCC	CSMF Accuracy	PCCC Improvement
GPT-4	0.61	0.79	↑ 0.03
GPT-3.5	0.58	0.74	↑ 0.14
InSilicoVA	0.44	0.74	↑ 0.01
InterVA-5	0.43	0.78	-

Note: Models sorted from highest to lowest PCCC. PCCC improvements are from model below.

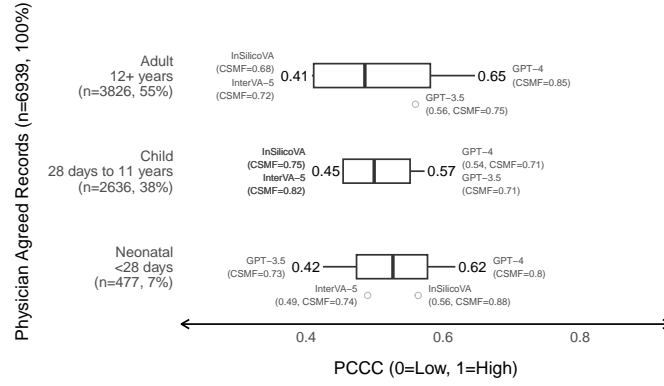


Fig. 2 Model performance by age group. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the adult (12 to 69 Years), child (28 days to 11 years), and neonatal (under 28 days) age groups. CSMF indicates CSMF accuracy.

3.2 Performance for 3826 Adult Records (12 to 69 years)

Across the adult age ranges, GPT-4 had the highest PCCC values at or above 0.59, followed by GPT-3.5, while InterVA-5 and InSilicoVA had the lowest PCCC values at or below 0.46. GPT-4 PCCC was between 0.61 and 0.72 for young to middle age ranges between 10 to 49 years, and at or below 0.62 for older age ranges between 50 to 69 years (Figure 3). Each age range had between 135 (4%) to 575 (15%) records with the 65-69 year age range having the most records (n=575, 15%), while other age ranges ranged from 4-9% of all records. Figure 4 shows the highest and lowest performing models by PCCC across 17 adult CODs excluding suicide due to the less notable 3 (<1%) records. The highest PCCC values were GPT-4 between 0.36 to 0.99 for 10 of 17 CODs (GPT-3.5, InterVA-5, and InSilicoVA within 0.05 for 3, 1, and 1 of these 10 CODs respectively), InSilicoVA for tuberculosis and road and transport injuries at 0.72 and 0.84 (GPT-4 and InterVA-5 within 0.05), and GPT-3.5 between 0.44 and 0.94 for 5 of 17 CODs (GPT-4 within 0.05 for malaria). The lowest PCCC values were InterVA-5 between 0 to 0.79 for 8 of 17 CODs (InSilicoVA and GPT-3.5 within 0.05 for cancers and unspecified infections respectively), InSilicoVA between 0.01 to 0.41 for 6 of 17 CODs (InterVA-5 within 0.05 for other cardiovascular diseases and diarrhoeal diseases), and GPT-3.5 at 0.39 for tuberculosis and 0.54 for road and transport injuries. Chronic respiratory diseases had the largest differences between minimum and maximum PCCC at 0.93. Maternal conditions, and road and transport injuries, had higher PCCC values above or at 0.67 (with the exception of GPT-3.5 for road and transportation injuries as an outlier), where there were small differences between minimum and maximum PCCC below or at 0.2. Ischemic heart disease and unspecified infections had PCCC values below or at 0.65, where there were small differences between minimum and maximum PCCC at or below 0.14. Each adult COD had between 27 (<1%) to 799 records (21%) with malaria (n=799, 21%), other noncommunicable diseases (n=414, 11%), and unspecified infections (n=389, 10%) making 42% of all records, and other CODs between 1-9% of all records. GPT-4 had the highest PCCC for both male and female records at 0.65 and 0.64 respectively, while all other models had PCCC at or below 0.6 (see Figure F11 in Appendix F).

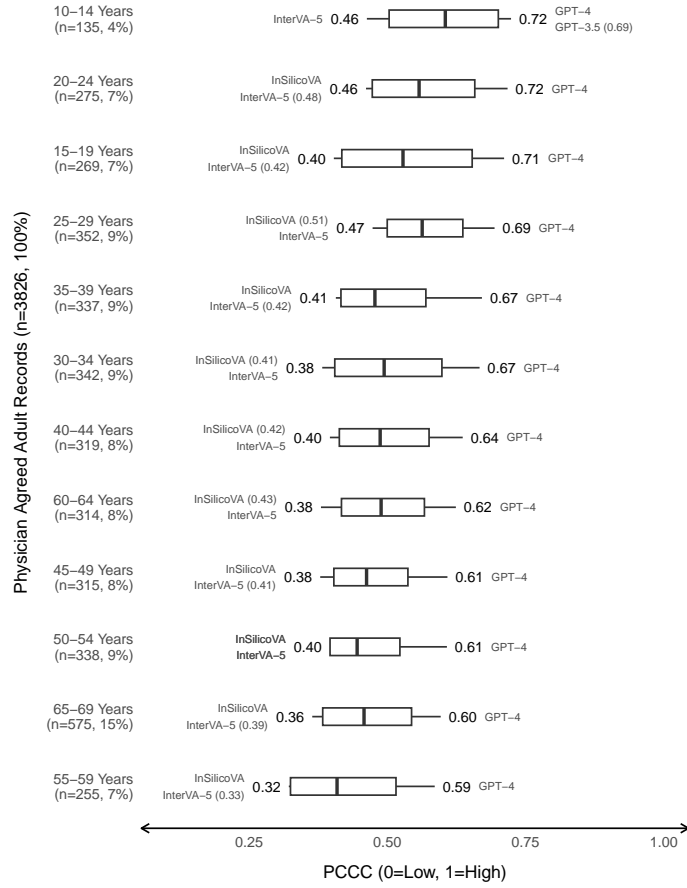


Fig. 3 Model performance for adult records by age range. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the adult age group (12 to 69 Years) by five-year age ranges. PCCC values are sorted by the highest to lowest PCCC for each age range. Only models with PCCC values within .05 of the highest and lowest PCCC are shown.

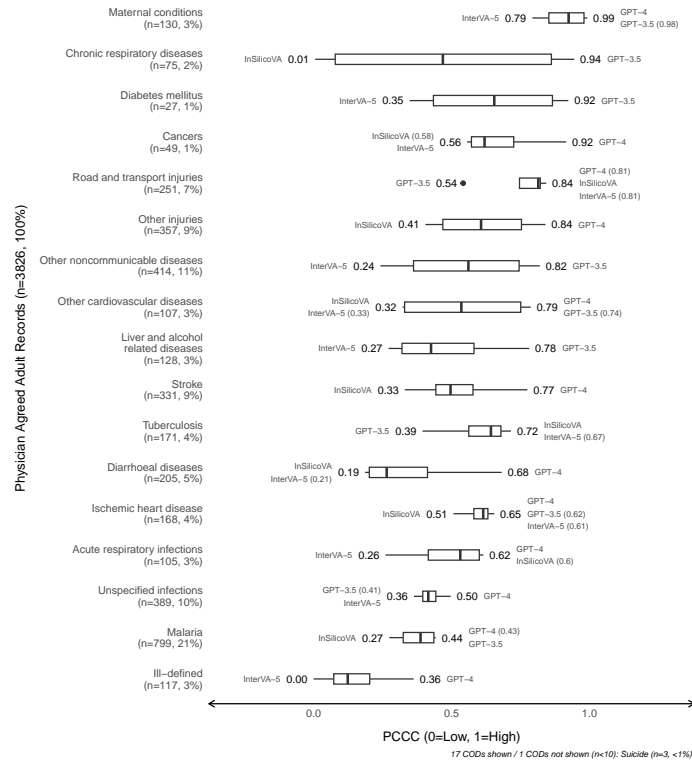


Fig. 4 Model performance for adult records by COD. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the adult age group (12 to 69 Years) by COD. PCCC values are sorted by the highest to lowest PCCC for each COD. Only models with PCCC values within .05 of the highest and lowest PCCC are shown. Suicide is not notable due to a small sample size of 3.

3.3 Performance for 2636 Child Records (28 Days to 11 Years)

Across the child age ranges, the highest PCCC was observed for GPT-4 at 0.59 and 0.66 for 1-5 years and 6-11 years (GPT-3.5 within 0.05), GPT-3.5 at 0.54 for 6-11 months, and InSilicoVA at 0.5 for 1-5 months (Figure 5). Each child age range had between 308 (12%) to 1633 (62%) records with most records in the 1-5 years range at 1633 records (62%) and the other age ranges consisting of 12-14% of all records. For the 8 child CODs (excluding congenital anomalies due to small sample size of 1 (<1%) record), the highest PCCC observed was for GPT-4 for 4 of 8 CODs, GPT-3.5 for 3 of 8 CODs (InSilicoVA within 0.05 for other infections), and InSilicoVA for pneumonia (Figure 6). The lowest PCCC across the 8 child CODs was observed for InSilicoVA for epilepsy, leukaemia, and other noncommunicable diseases and malaria, InterVA-5 for pneumonia, nutritional deficiencies, and other infections. GPT-3.5, InSilicoVA, and InterVA-5 all had similar PCCC values greater than 0.8 as the lowest PCCC for injuries. Epilepsy, leukaemia, and other noncommunicable disease had the largest difference between minimum and maximum PCCC at 0.68, while Ill-defined had the next largest difference at 0.67 with InSilicoVA and InterVA-5 at 0 PCCC. Malaria and other infections had low PCCC values below 0.58 across models with small differences between minimum and maximum PCCC at 0.18 and 0.14 respectively. Injuries and diarrhoeal diseases had high PCC values above 0.6 across models with small differences between minimum and maximum PCC at 0.14 and 0.3 respectively. Each of the 8 child CODs had between 11 (<1%) to 1382 (52%) records with malaria (n=1382, 52%), other infections (n=667, 25%), and diarrhoeal diseases (n=175, 7%) making 84% of all records. Nutritional deficiencies had less than 1% of all records, while other CODs had between 1-3% of all records. GPT-3.5 had the highest PCCC for both male and female records at 0.56 and 0.58 with GPT-4 within 0.05 PCCC at 0.55 and 0.54 respectively, while all other models had PCCC below 0.5 (see Figure F12 in Appendix F).

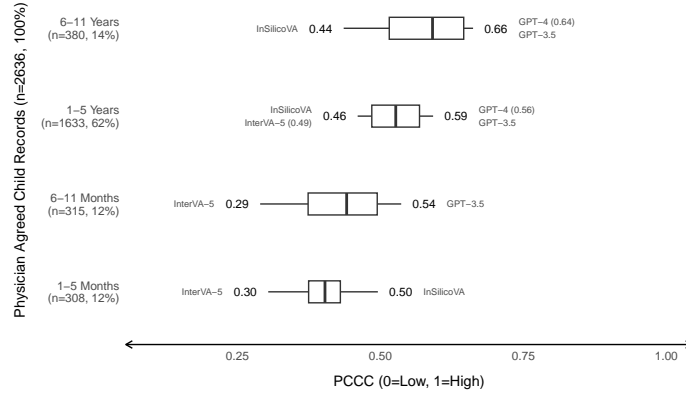


Fig. 5 Model performance for child records by age range. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the child age group (28 days to 11 years) by five-year age ranges. PCCC values are sorted by the highest to lowest PCCC for each age range. Only models with PCCC values within .05 of the highest and lowest PCCC are shown.

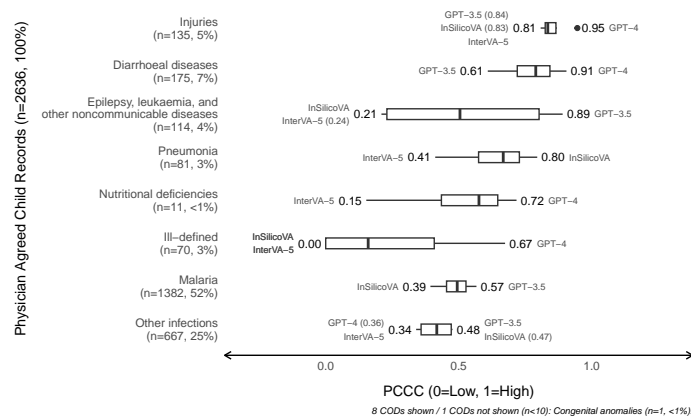


Fig. 6 Model performance for child records by COD. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the child age group (28 days to 11 years) by COD. PCCC values are sorted by the highest to lowest PCCC for each COD. Only models with PCCC values within .05 of the highest and lowest PCCC are shown. Congenital anomalies is not notable due to small sample size of 1.

3.4 Performance for 477 Neonatal Records (Under 28 Days)

GPT-4 had the highest PCCC for 0-6 day and 7-27 day neonatal age ranges at 0.6 and 0.7 respectively, while GPT-3.5 had the lowest PCCC across all neonatal age ranges as seen in Figure 7. There were large differences between minimum and maximum PCCC for 7-27 days at 0.33, and small differences for 0-6 days at 0.16. Most records were in the 0-6 day age range at 395 (83%) records, while the rest were in the 7-27 day age range at 82 (17%) records. Across 5 neonatal CODs (excluding congenital anomalies and other due to small sizes of 2 (<1%) and 5 (1%) respectively), the highest PCCC was observed for GPT-4 for 3 of the 5 CODs (GPT-3.5 identical for prematurity and low birthweight), GPT-3.5 for 2 of the 5 CODs (InSilicoVA identical for stillbirth), and InSilicoVA for neonatal infections (Figure 8). Stillbirth had small differences between minimum and maximum PCCC at 0.07. The other 4 CODs had large differences between minimum and maximum PCCC ranging from 0.46 to 0.64. Each neonatal COD had between 23 (5%) to 172 (38%) records, with stillbirth (n=172, 36%), birth asphyxia and birth trauma (n=103, 22%), and neonatal infections (n=99, 21%), and prematurity and low birthweight (n=73, 15%) making 94% of all records, while the rest are in ill-defined. GPT-4 had the highest PCCC for both female and male records at 0.62, while all other models had PCCC at or below 0.56 (see Figure F13 in Appendix F).

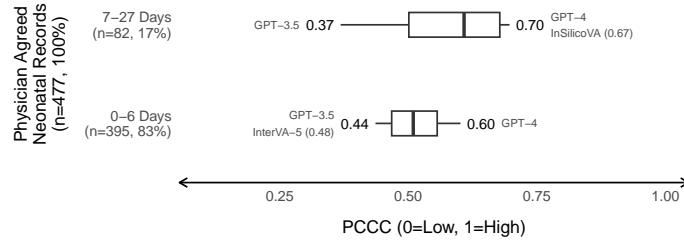


Fig. 7 Model performance for neonatal records by age range. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the neonatal age group (under 28 days) by five-year age ranges. PCCC values are sorted by the highest to lowest PCCC for each age range. Only models with PCCC values within .05 of the highest and lowest PCCC are shown.

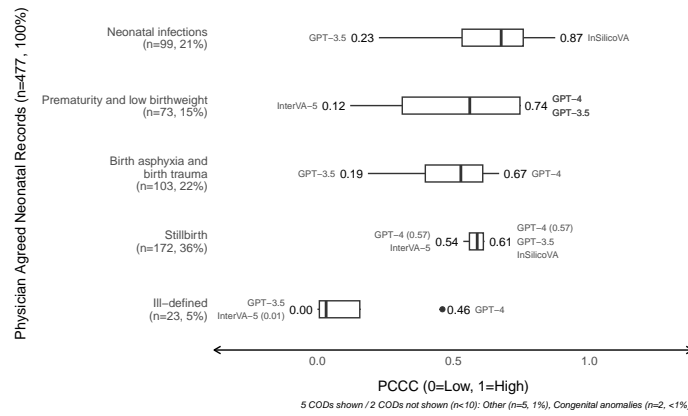


Fig. 8 Model performance for neonatal records by COD. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the neonatal age group (under 28 years) by COD. PCCC values are sorted by the highest to lowest PCCC for each COD. Only models with PCCC values within .05 of the highest and lowest PCCC are shown. Congenital anomalies and other are not notable due to small sample sizes of 2 and 5 respectively.

4 Discussion

This section discusses and summarizes the results from Section 3. Advantages and disadvantages of using GPT-3.5, GPT-4, InterVA-5, and InSilicoVA models for assigning CODs are discussed in Sections 4.1 and 4.2. Limitations of the study are mentioned in Section 4.3, while opportunities and future work are detailed in Section 4.4.

4.1 Advantages

This section identifies advantages of performant models for assigning CODs. Section 4.1.1 details the strategic use of models for particular CODs. Section 4.1.2 details the resource efficiency of GPT and InSilicoVA models for assisting in physician COD assignment. Section 4.1.3 notes the strength of using natural language text in GPT models compared to structured data (e.g. questionnaires) for physician COD assignment.

4.1.1 Performant for Particular Causes of Death

At the population level, overall performances for all causes were similar ($0.7 \leq \text{CSMF} \leq 0.79$), but not close (≥ 0.8 CSMF), to physicians at 0.74-0.79 CSMF. At the individual level, performance by PCCC varies across CODs, and for most CODs, GPT models (GPT-4 and GPT-3) performed better than InSilicoVA and InterVA-5 (Table 2). However, there were CODs where InSilicoVA performed better. For example, neonatal infections at 0.87 PCCC versus 0.23 for GPT-3.5, and adult tuberculosis at 0.72 versus 0.39 for GPT-3.5. For CODs with high performance (≥ 0.8 PCCC) (Table 2), the results suggest that GPT models (and InSilicoVA for particular CODs) may assign CODs that are close physicians, when physicians would agree on the COD. Thus, when applying models to assign CODs, it may help to target CODs with a combination of models that performed well or close to physician assignment.

Across age ranges, GPT and InSilicoVA models had performances below 0.8 PCCC, where ages 10-24 years and 7-27 days had the highest performance (≥ 0.7 PCCC). For adult age ranges, performance generally decreased as age increased, which suggested that models had difficulty assigning CODs for older than younger adults (Figure 3). For child and neonatal age ranges, the performance improves as the age increases, suggesting less difficulty in COD assignment when children and neonates are more developed (Figures 5 and 7). As the models did not perform well for any particular age range, it may not be suggested to apply specific models to target cases by age range. However, the general patterns (increases and decreases of performance in relation to age) are useful in comparing expected patterns in relation to physician assignment.

4.1.2 Resource Efficient

The models in this study can assist physicians in assigning CODs in a variety of ways due to low costs and speed of COD assignment. Similar to differential diagnoses, GPT and InSilicoVA models can offer more alternative COD assignments for physicians to consider, [38], which can potentially help lower the number of records with ill-defined

Table 2 Models with performances close to physician COD assignment (≥ 0.8 PCCC) across age groups

Cause of Death	Cases	Best Model	PCCC
Adult (n=3826, 1303 (34%) ≥ 0.8 PCCC)			
Maternal conditions	130 (3%)	GPT-4	0.99
Chronic respiratory diseases	75 (2%)	GPT-3.5	0.94
Diabetes mellitus	27 (1%)	GPT-3.5	0.92
Cancers	49 (1%)	GPT-4	0.92
Road and transport injuries	251 (7%)	InSilicoVA	0.84
Other injuries	357 (9%)	GPT-4	0.84
Other noncommunicable diseases	414 (11%)	GPT-3.5	0.82
Child (n=2636, 505 (19%) ≥ 0.8 PCCC)			
Injuries	135 (5%)	GPT-4	0.95
Diarrhoeal diseases	175 (7%)	GPT-4	0.91
Epilepsy, leukaemia, and other noncommunicable diseases	114 (4%)	GPT-3.5	0.89
Pneumonia	81 (3%)	InSilicoVA	0.8
Neonatal (n=477, 99 (21%) ≥ 0.8 PCCC)			
Neonatal infections	99 (21%)	InSilicoVA	0.87

Note: Best models sorted from highest to lowest PCCC per age group.

causes or reduce disagreement in physicians. At the time of this study, running GPT-3.5 cost $\sim \$1.6$ USD ($\$0.5$ per one million tokens), GPT-4 cost $\sim \$115$ USD ($\$30$ per one million tokens), and InSilicoVA had no costs on 6939 physician agreed records [67]. These costs are likely lower than physicians (e.g. less than $\$3$ USD per house in India [15, 16]), while over 10,000 records can be coded in under a day. When physicians are unavailable, GPT and InSilicoVA models can be a cost-efficient alternative to code large amounts of records for population estimates of CODs. However, care needs to be taken to apply these models only for certain CODs where models perform well, such as in Table 2. In addition, these models can also help divert physician resources to cases that are more difficult to code or require more attention. For example, physicians can simply check cases, such as road traffic injury where models performed well at 0.84 PCCC, while spending more time on cases that related to acute respiratory infections, where the models performed poorly at 0.62 PCCC (Figure 4).

4.1.3 Natural Language Flexibility

All models did not require training data to assign CODs, which allowed them to be used without domain expertise and supplying training datasets. The main advantage to GPT-3.5 and GPT-4 was the use of natural language text as input and output. Compared to InterVA-5 and InSilicoVA, GPT models were able to assign COD codes in ICD-10, as physicians do, and potentially assign CODs in more broad categories depending on the prompts. In comparison, InterVA-5 and InSilicoVA relied on structured input and output data from WHO VA 2016 questionnaires, and assigned CODs

in WHO VA 2016 codes only. This required that these codes and forms be maintained with conversions between different form (e.g. WHO VA 2012 to WHO VA 2016) and code standards (e.g. WHO VA 2016 to ICD-10), which reduces interoperability and comparability when other models and VA systems do not use the same or interchangeable standards. Thus, GPT models did not require strict formats for training and testing data, which can capture latent and more ambiguous patterns (e.g. health-seeking behaviours and social issues) outside the scope of WHO VA codes and forms [26, 28]. For example, GPT-3.5 and GPT-4 had higher performance (+0.14-0.67 PCCC) than InterVA-5 and InSilicoVA for more ambiguous CODs (e.g. other/unspecified infections, ill-defined, other cardiovascular diseases). GPT models also performed better (+0.57 PCCC) on CODs with a small number of cases, such as nutritional deficiencies (n=11) and diabetes mellitus (n=27), which may not have enough cases for questionnaires to capture statistical patterns, but may possibly have richer contextual information from articles, web sources, or books that GPT models can leverage.

4.2 Disadvantages

This section discusses the disadvantages of GPT models for COD assignment. Section 4.2.1 identifies issues in reproducing GPT outputs for repeated runs on the same records and lack of up-to-date information, while Section 4.2.2 discusses the resource intensive infrastructure required by GPT and its relation to data privacy.

4.2.1 Reproducibility and Timeliness

The GPT models in this study had the temperature parameter set to 0 for more reproducible results. A short experiment in Appendix G revealed that GPT-3.5 assigns the same COD for the same record only more than 60% of the time, based on repeated runs on a sample of 100 records. Although more extensive testing is needed, this suggests that GPT models do not always assign the COD for the same case on multiple runs, which may pose issues in reproducibility and reliability. For example, GPT models may achieve correct COD assignments solely due to random chance, but are difficult to test with large numbers (e.g. 10,000) of reruns due to costs (e.g. costs increased 10 fold per record when rerun 10 times). In comparison, InterVA-5 and InSilicoVA are open source and free, and assign deterministic CODs with probabilities for each alternative COD, which offers more reproducible and reliable COD assignments despite lower performance overall. In addition, all models were trained on historical data up to particular points in time, which may not utilize the most up-to-date data available (e.g. latest online articles, social media, or books for GPT models).

4.2.2 Infrastructure and Data Privacy

GPT-3.5 and GPT-4 models required large computing infrastructure to train and run, which was not possible to run on local computers, or setup due to costs. This poses issues with data privacy as sensitive data (e.g. identifying information) needs to be sent to company servers, which can be collected by companies (e.g. OpenAI) and misused [68]. For example, GPT models use prompts, which contain the narrative data, to assign CODs. The data in the prompts may be unknowingly collected and misused by

companies (e.g. companies) or their users (e.g. malicious prompts) [69, 70]. In contrast, InterVA-5 and InSilicoVA can be run on local computers, which allows data to stay with the owner to protect data privacy, without reliance on external services.

4.3 Limitations

This section identifies limitations in this research in the context of GPT models. Section 4.3.1 identifies the omission of ICD-10 performance evaluations. Section 4.3.2 discusses data limitations, such as small samples, exclusion of disagreements, and exploration of incorrectly assigned cases. Section 4.3.3 mentions the need for parameter tuning and evaluation of consistency and multiple COD assignments.

4.3.1 ICD-10 Performance Evaluation

For the scope of this study, all models were evaluated for their performance in broad CGHR-10 COD categories as opposed to more specific ICD-10 codes. However, in practical cases, physicians assign more specific ICD-10 codes rather than broader COD categories. InterVA-5 and InSilicoVA assigned broader WHO VA codes, and were unable to assign ICD-10 codes, as the number of cases for specific ICD-10 codes may not have enough cases for training statistical models. GPT models were able to assign ICD-10 codes, but may possibly result in lower performance as even physicians do not agree completely on ICD-10 codes, and broader categories (CMEA-10 codes in Additional file 2) were used to assign equivalency or agreement.

4.3.2 Small Samples, Disagreements, and Misclassifications

Performance evaluations and analyses were omitted for CODs with less than 10 cases (e.g. congenital anomalies, suicide), in which models may perform well on, but have limited evidence to make conclusive insights on performance. In this study, only records where physicians agreed on the COD assignment were included in performance evaluations. However, the performance of GPT-4 only dropped slightly from 0.61 (agreed) to 0.53 (disagreed) PCCC while records almost doubled, which suggests that GPT models may potentially be able to assign agreeable CODs without reconciliation or adjudication for cases where physicians disagreed (Figure F10). In relation, GPT may be used to explore prompts that may possibly reconcile or adjudicate records in disagreement. Finally, an exploration of misclassifications was not conducted for this study, but may yield useful insights. For example, a non-comprehensive exploration was conducted in Appendix H on misclassified GPT-4 records for neonatal infections, which found potential issues with the categorization of CGHR-10 codes, order of information in narratives, and guidelines of COD assignments. More records may also provide more conclusive evidence of model performance results as 6939 records may be inadequate evidence at the country level compared to more comprehensive studies (e.g. the million death study [16]).

4.3.3 Model Tuning, Consistency, and Multiple Outputs

GPT-3.5 and GPT-4 models used default parameters with the exception of setting the temperature to 0 for more consistent results. However, the temperature and other

potential settings may be adjusted to possibly improve performance [59]. In addition, GPT models may possibly produce inconsistent results even with the temperature set to 0 as discussed in Section 4.2.1. Thus, it is important to also test the reliability and consistency of GPT outputs to avoid coincidental results due to randomness [71–73]. InterVA-5 and InSilicoVA were able to provide multiple COD assignments with probabilities for each. GPT models can be prompted to produce more than one COD assignment, but was not explored in this study. This may be useful to evaluate the performance of suggested alternative COD assignments, which can help physicians reach agreement or reduce ill-defined assignments.

4.4 Opportunities

This section discusses research opportunities to improve GPT models for assigning CODs. Section 4.4.1 discusses the potential to improve GPT models with prompt engineering and exploration of misclassified records. Section 4.4.2 identifies an opportunity to integrate GPT, InterVA-5, and InSilicoVA models into VA systems for improving physician COD assignment.

4.4.1 Prompt Engineering and Custom Models

Prompt engineering, the act of designing prompts to guide GPT models for better results [74], presents an important research opportunity that may improve performance of GPT models for COD assignment. As mentioned in Section 4.3.2 and exemplified in Appendix H, an analysis of misclassified records may yield insights on adjusting prompts to assign more correct CODs in relation to physicians. In addition, subsequent prompts and examples can be used to add in correctional instructions and refine results, while additional information from the questionnaire and physician VA manuals may add better context [75]. Sensitivity analyses may be conducted to assess the effects on performance and consistency of results from modified prompts on a COD basis. GPT models may also be customized to specific domains or contexts, where objectives, behaviours, extra data, privacy, and evaluation tests can be adjusted to produce custom models that perform better in targeted domains or circumstances [76].

4.4.2 Computer Assisted Verbal Autopsy

Another research opportunity is in the integration of GPT, InterVA-5, and InSilicoVA models into VA systems to assist physicians in COD assignment. In dual-coded VA systems (described in Section 2.1), two physicians are randomly assigned to each record and require second inspections of each other’s assignment (reconciliation) and evaluation by a third more senior physician if their assignments do not agree. As mentioned in Section 4.1.2, suggestion of alternative assignments from GPT and InSilicoVA models potentially reduces the disagreement between physicians, and ill-defined records, while allowing physicians to focus on more difficult records. Thus, model suggestions can be integrated into VA systems by presenting model suggestions to physicians after their initial COD assignment, which allows them to consider alternative assignments and possibly revise their assignments based on the suggestions (Figure 9). Our future

work will assess the effects of these model suggestions on physician assignment outcomes (e.g. increase in agreed records, reduction of ill-defined deaths). In preparation, we have integrated GPT-4, InterVA-5, and InSilicoVA model suggestions into our HEAL-SL study for after survey round 2 [34].

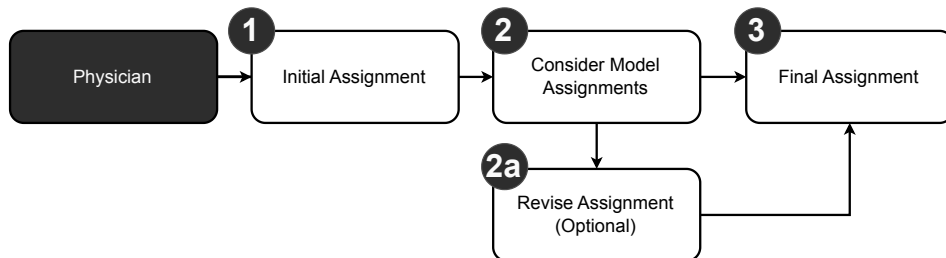


Fig. 9 Addition of model suggestions into physician assignment process. GPT, InterVA-5, and InSilicoVA models can suggest COD assignments to consider, providing the option to revise or proceed with their initial assignment. The additional consideration potentially reduces disagreement between physicians and ill-defined deaths.

5 Conclusion

TO DO.

Supplementary information. Additional files were used to supplement this paper:

- Additional file 1: Centre for Global Health Research 10 (CGHR-10) codes. Codes grouping ICD-10 code ranges into generalized categories. (.csv)
- Additional file 2: Central Medical Evaluation Agreement 10 (CMEA-10) codes. ICD-10 code ranges considered in physician agreement. (.csv)

Acknowledgments.

Declarations

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article (and its additional files).

Appendix A Case Study Methods

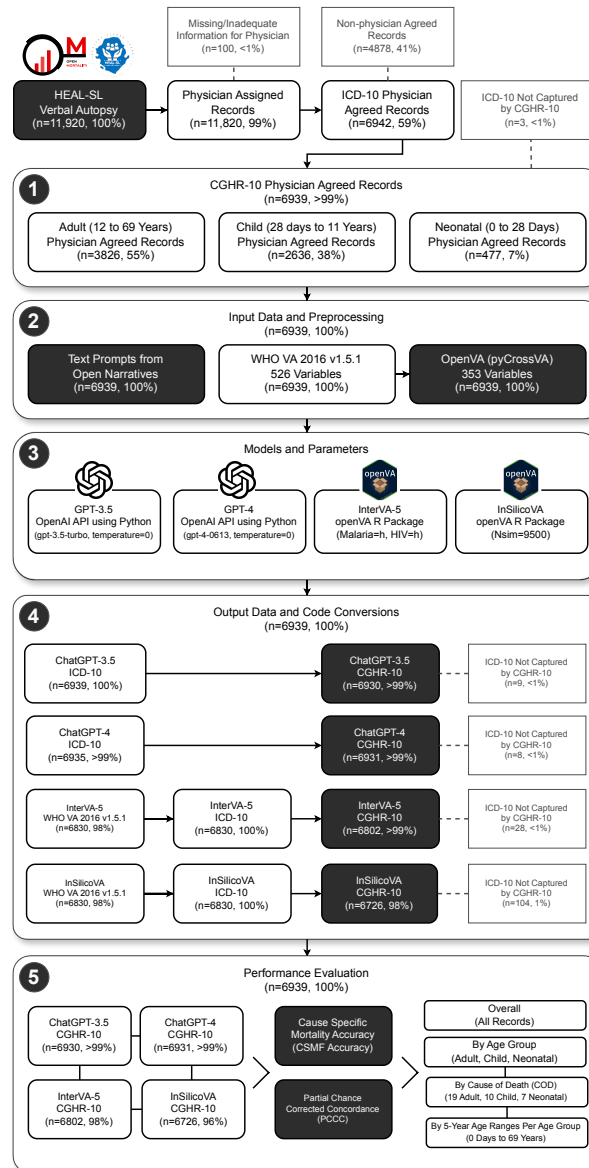


Fig. A1 Case study methods. VA records in Sierra Leone between 2019-2022 from the HEAL-SL study were filtered for physician agreed records, and pre-processed for COD assignment by GPT-3.5, GPT-4, InterVA-5 and InSilicoVA models. The output models were evaluated with CSMF Accuracy and PCCC overall, by age group, and by COD and five-year age ranges for each age group.

Appendix B Physician Agreed Verbal Autopsy Records

The following figures visualize the distribution of all physician agreed records by age groups (Figure B2) and 5-year age ranges (Figure B3) in Sierra Leone from 2019 to 2022.

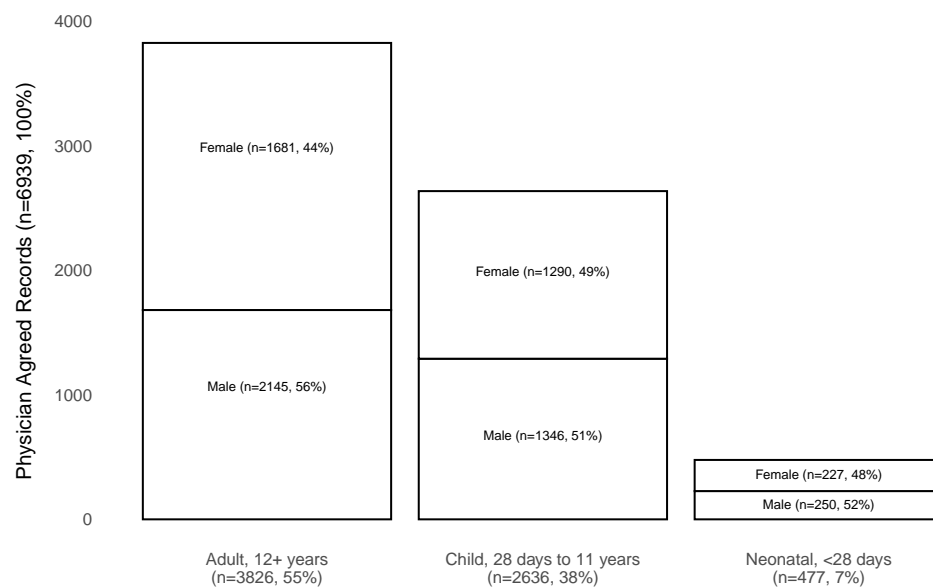


Fig. B2 Number of physician agreed VA records by adult, child, and neonatal age groups in Sierra Leone from 2019 to 2022.

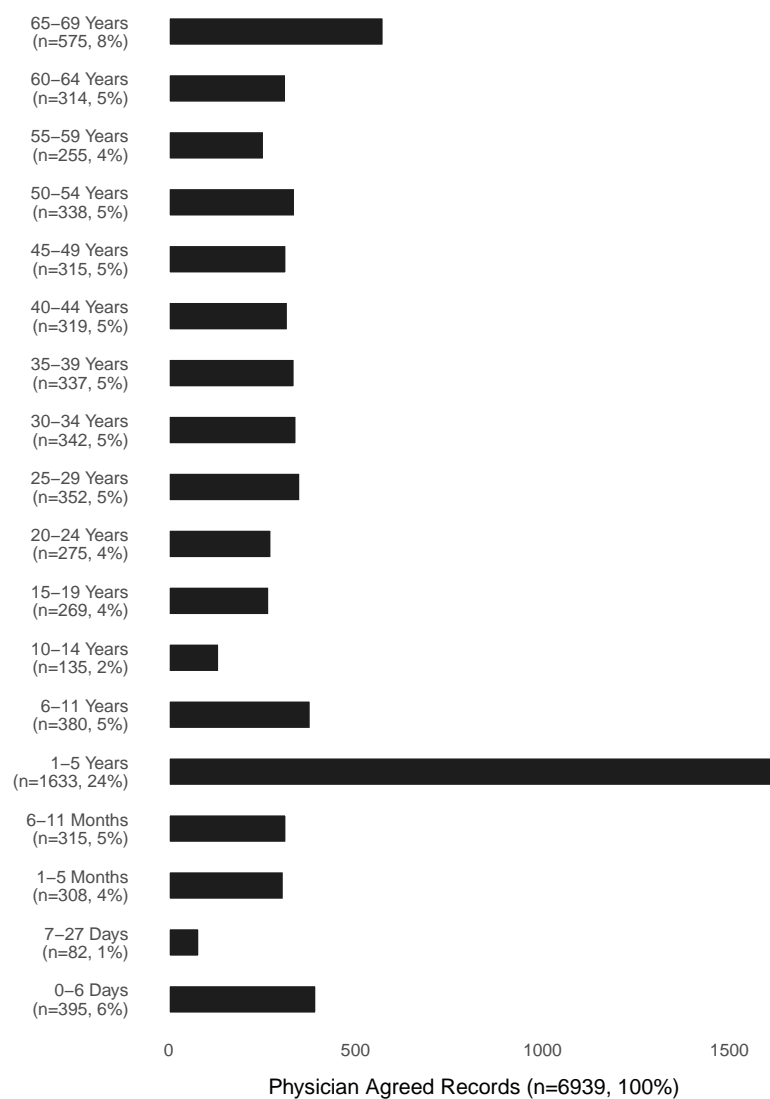


Fig. B3 Number of physician agreed VA records by 5-year age ranges in Sierra Leone from 2019 to 2022.

Appendix C Adult Physician Agreed Verbal Autopsy Records (12 to 69 Years)

The following figures visualize the distribution of adult physician agreed records by 5-year age ranges (Figure C4) and CGHR-10 COD code in Sierra Leone from 2019 to 2022 (Figure C5).

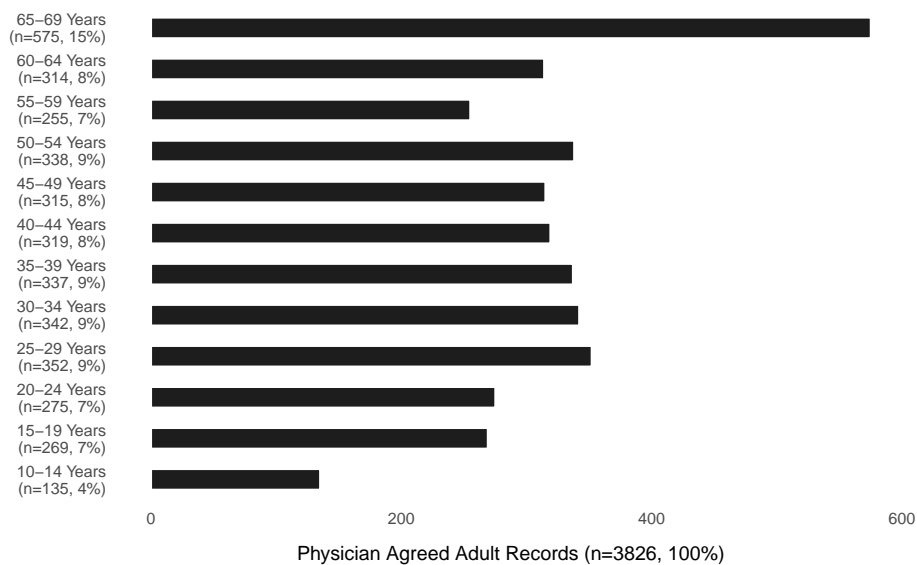


Fig. C4 Number of physician agreed adult (12 to 69 years) VA records by 5-year age ranges in Sierra Leone from 2019 to 2022.

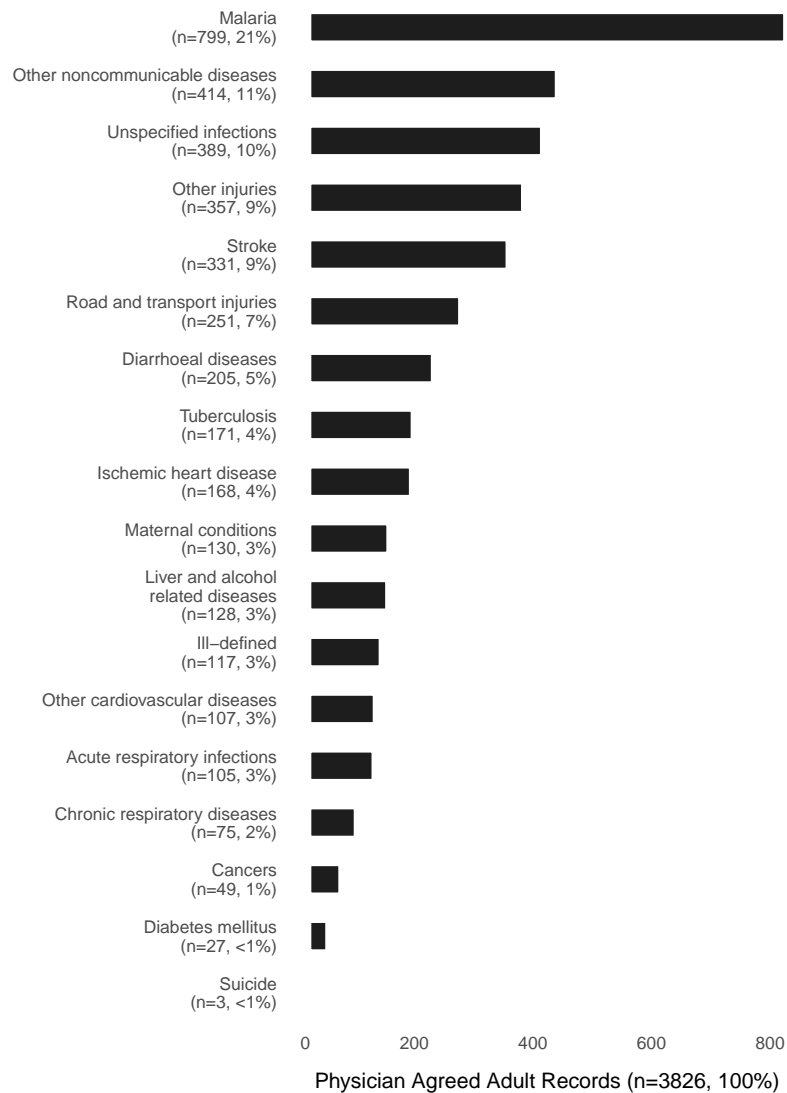


Fig. C5 Number of physician agreed adult (12 to 69 years) VA records by CGHR-10 COD code in Sierra Leone from 2019 to 2022.

Appendix D Child Physician Agreed Verbal Autopsy Records (28 Days to 11 Years)

The following figures visualize the distribution of child physician agreed records by 5-year age ranges (Figure D6) and CGHR-10 COD code in Sierra Leone from 2019 to 2022 (Figure D7).

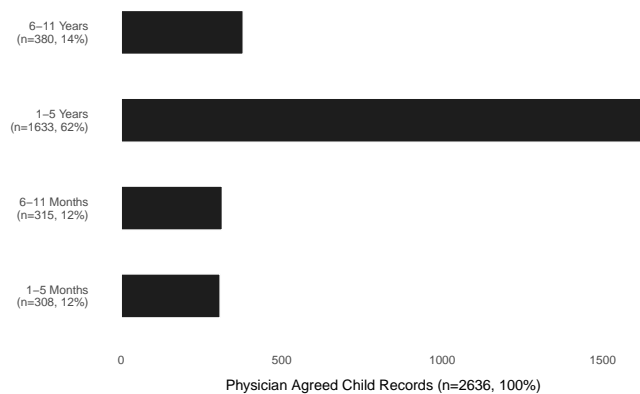


Fig. D6 Number of physician agreed child (28 days to 11 years) VA records by 5-year age ranges in Sierra Leone from 2019 to 2022.

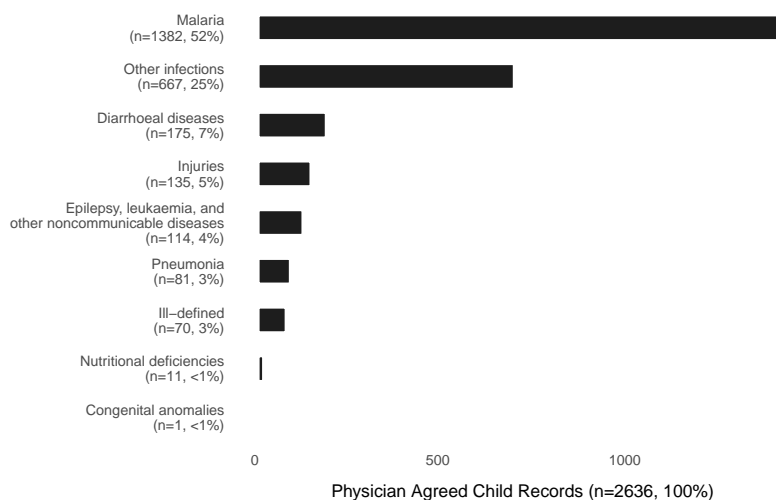


Fig. D7 Number of physician agreed child (28 days to 11 years) VA records by CGHR-10 COD code in Sierra Leone from 2019 to 2022.

Appendix E Neonatal Physician Agreed Verbal Autopsy Records (Under 28 Days)

The following figures visualize the distribution of neonatal physician agreed records by 5-year age ranges (Figure E8) and CGHR-10 COD code in Sierra Leone from 2019 to 2022 (Figure E9).



Fig. E8 Number of physician agreed neonatal (less than 28 days) VA records by 5-year age ranges in Sierra Leone from 2019 to 2022.

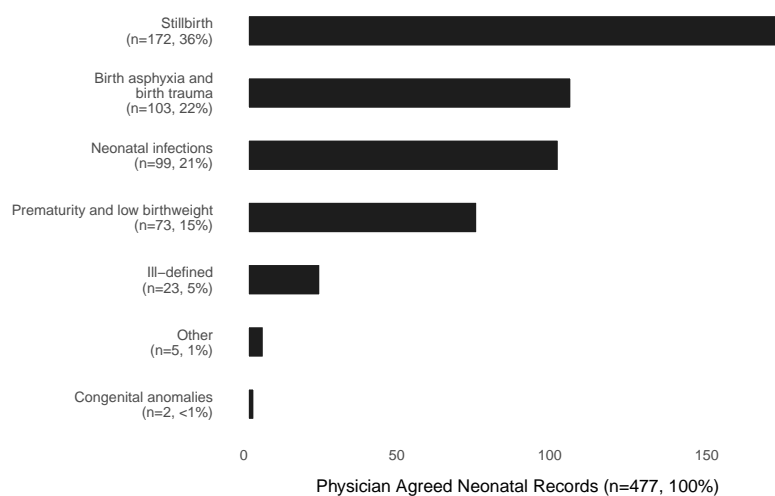


Fig. E9 Number of physician agreed neonatal (less than 28 days) VA records by CGHR-10 COD code in Sierra Leone from 2019 to 2022.

Appendix F Performance By Other Variables

The following figures show the model performance by PCCC for all records and physician agreed records (Figure F10), and the performance of models by PCCC across sex for the adult (12 to 69 years), child (28 days to 11 years), and neonatal (under 28 days) age groups in Figures F11, F12, and F13 respectively.

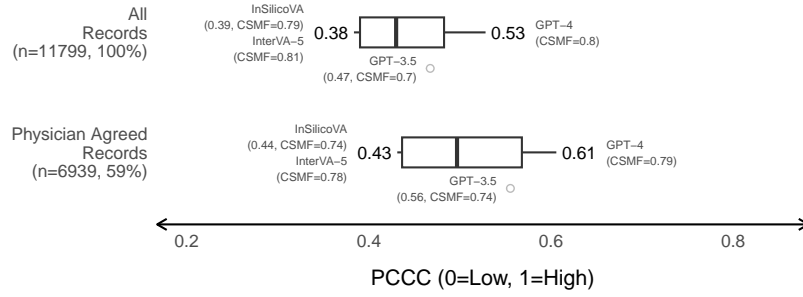


Fig. F10 Model performance for all records versus physician agreed records. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs for all records and physician agreed records. PCCC values are sorted by the highest to lowest PCCC.

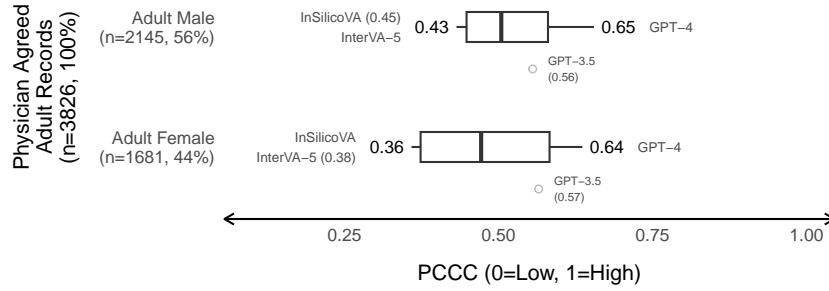


Fig. F11 Model performance for adult records by sex. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the adult age group (12 to 69 years) by sex. PCCC values are sorted by the highest to lowest PCCC.

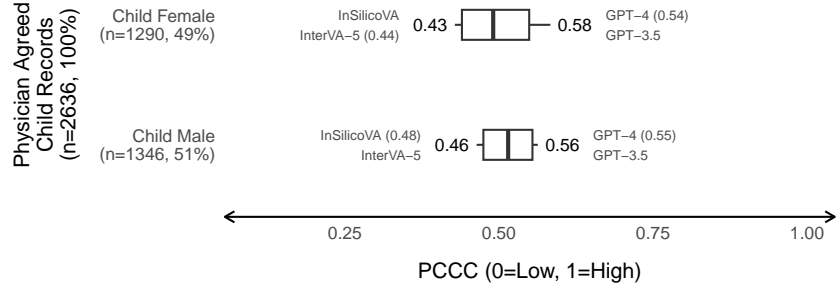


Fig. F12 Model performance for child records by sex. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the child age group (28 days to 11 years) by sex. PCCC values are sorted by the highest to lowest PCCC.

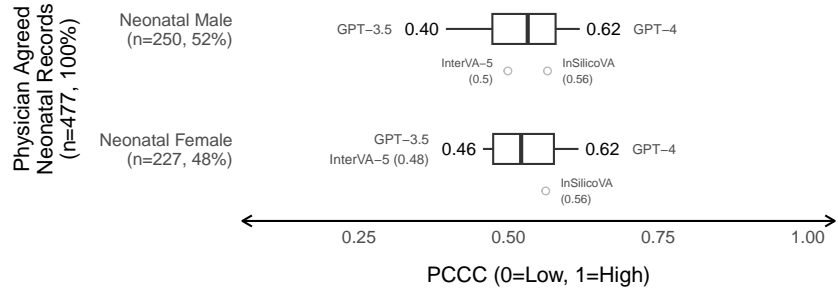


Fig. F13 Model performance for neonatal records by sex. GPT-3.5, GPT-4, InterVA-5, and InSilicoVA model performance for assigning CGHR-10 CODs in the neonatal age group (under 28 days) by sex. PCCC values are sorted by the highest to lowest PCCC.

Appendix G Experiment on Repeated Runs of GPT-3.5

A short experiment was conducted to test the consistency of GPT-3.5 outputs repeated on the same record. 100 records, sampled randomly with approximately equal proportions across age groups, CODs, and survey rounds 1 and 2, were used to test repeated runs of GPT-3.5. Each record from the 100 records was rerun 10 times through GPT-3.5, resulting in ten COD outputs per record. The ICD-10 codes were then converted to CGHR-10 codes and tested for consistency, where completely inconsistent results had different ICD-10 or CGHR-10 codes for each of the 10 reruns (1 times+), and completely consistent results had the same ICD-10 or CGHR-10 code for all 10 reruns (10 times), on the same record.

The results are shown in Table G1. For all 100 records, GPT-3.5 assigns the same ICD-10 and CGHR-10 code for the same record 5 times or more out of 10. For 66 and 79 records, GPT-3.5 assigns the same ICD-10 and CGHR-10 code respectively for each record. This number increases to 94 (from 66) and 96 (from 79) when reducing the number of times out of 10 that GPT-3.5 assigns the same ICD-10 and CGHR-10 code respectively. Thus, GPT-3.5 does not always produce the same outputs when repeated on the same record (10 times out of 10), even when the temperature is set to 0, but does so for more than half the records. For most records (more than 90%), GPT-3.5 will produce the same outputs for the same record 7 times or more out of 10.

Table G1 Number of records with same GPT-3.5 outputs based on 10 repeated reruns of 100 records

Times with Same GPT-3.5 Outputs	ICD-10 Records	CGHR-10 Records
1 times+ (inconsistent)	100	100
2 times+	100	100
3 times+	100	100
4 times+	100	100
5 times+	100	100
6 times+	94	96
7 times+	92	94
8 times+	86	91
9 times+	79	86
10 times (consistent)	66	79

Note: The 100 records were sampled proportionally for age, cause of death, and survey rounds 1 and 2.

Appendix H Exploration of Neonatal Infections

An exploration of neonatal infections (n=99, 21% of 477 records) was done to understand the low performance of GPT models (0.23 PCCC) for neonatal infections, and high performance of InSilicoVA (0.87 PCCC). In Table H2, about half the records were assigned correctly, and a majority (n=33, 33%) of the other records were misclassified as other, while prematurity and low birthweight, birth asphyxia & birth trauma, and ill-defined make up the rest. On closer inspection of the 49 records with misclassified assignments, the ICD-10 code R50 was assigned in 20 records. R50 falls under unspecified infections in the adult CGHR-10 category, but in the other category for neonates. B50 was assigned in 4 records, falling under malaria, but a similar B54 falls under neonatal infections. P81 was assigned in 3 records, referring to fever of unknown origin, which falls under other, and P07 was assigned in 7 records, falling under prematurity and low birthweight.

In most misclassified records, there is mention of infections, but the misclassifications occur due to the finer details of the ICD-10 code classifications, the categorization decisions of the CGHR-10 codes, and missing information from the questionnaire. For R50 misclassifications, GPT may have confused descriptions across adult and neonatal age groups. Using the same definition of R50, but in the context of neonates, may result in codes closer to neonatal infections (e.g. B54). For B50 misclassifications, the similar B54 was categorized in CGHR-10 as neonatal infections, but B50 was categorized as other. P81 refers to fever of unknown origin, which may be difficult to differentiate between infection and other causes without information from the questionnaire. P07 refers to prematurity and low birthweight, where GPT initially assigned P07 as the age of the neonate was mentioned first, but later mentions infections as an alternative following the order of information in the narratives. Thus, it may be possible to improve the performance GPT models using better prompts based on the context of VA manuals and CGHR-10 codes, and by also including questionnaire information in the prompts.

Table H2 CGHR-10 cause of death assignment from GPT-4 for records coded as neonatal infections by physicians

GPT-4 Assigned Cause of Death (CGHR-10)	Records
Neonatal infections	50 (51%)
Other	33 (33%)
Prematurity and low birthweight	9 (9%)
Birth asphyxia & birth trauma	5 (6%)
Ill-defined	2 (2%)
Total	99 (100%)

References

- [1] World Health Organization.: Non Communicable Diseases: Key Facts. Available from: <https://www.who.int/news-room/fact-sheets/detail/noncommunicable-diseases>.
- [2] Benziger CP, Roth GA, Moran AE. The Global Burden of Disease Study and the Preventable Burden of NCD. *Global Heart*. 2016 Dec;11(4):393–397. <https://doi.org/10.1016/j.gheart.2016.10.024>.
- [3] Lawn JE, Kerber K, Enweronu-Laryea C, Cousens S. 3.6 Million Neonatal Deaths—What Is Progressing and What Is Not? *Seminars in Perinatology*. 2010 Dec;34(6):371–386. <https://doi.org/10.1053/j.semperi.2010.09.011>.
- [4] Lassi ZS, Bhutta ZA. Community-based Intervention Packages for Reducing Maternal and Neonatal Morbidity and Mortality and Improving Neonatal Outcomes. *Cochrane Database of Systematic Reviews*. 2015;(3). <https://doi.org/10.1002/14651858.CD007754.pub3>.
- [5] Liu NH, Daumit GL, Dua T, Aquila R, Charlson F, Cuijpers P, et al. Excess Mortality in Persons with Severe Mental Disorders: A Multilevel Intervention Framework and Priorities for Clinical Practice, Policy and Research Agendas. *World Psychiatry*. 2017;16(1):30–40. <https://doi.org/10.1002/wps.20384>.
- [6] Ewig S, Torres A. Community-Acquired Pneumonia as an Emergency: Time for an Aggressive Intervention to Lower Mortality. *European Respiratory Journal*. 2011 Aug;38(2):253–260. <https://doi.org/10.1183/09031936.00199810>.
- [7] World Health Organization. SCORE for Health Data Technical Package: Global Report on Health Data Systems and Capacity, 2020; 2021. Available from: <https://www.who.int/publications/i/item/9789240018709>.
- [8] de Savigny D, Riley I, Chandramohan D, Odhiambo F, Nichols E, Notzon S, et al. Integrating Community-Based Verbal Autopsy into Civil Registration and Vital Statistics (CRVS): System-Level Considerations. *Global Health Action*. 2017 Jan;10(1):1272882. <https://doi.org/10.1080/16549716.2017.1272882>.
- [9] Thomas LM, D’Ambruso L, Balabanova D. Verbal Autopsy in Health Policy and Systems: A Literature Review. *BMJ Global Health*. 2018 May;3(2):e000639. <https://doi.org/10.1136/bmjgh-2017-000639>.
- [10] Rampatige R, Mikkelsen L, Hernandez B, Riley I, Lopez AD. Systematic Review of Statistics on Causes of Deaths in Hospitals: Strengthening the Evidence for Policy-Makers. *Bulletin of the World Health Organization*. 2014 Sep;92:807–816. <https://doi.org/10.2471/BLT.14.137935>.

- [11] Adair T. Who Dies Where? Estimating the Percentage of Deaths That Occur at Home. *BMJ Global Health*. 2021 Sep;6(9):e006766. <https://doi.org/10.1136/bmjgh-2021-006766>.
- [12] World Health Organization. Verbal Autopsy Standards: 2022 WHO Verbal Autopsy Instrument; 2023. Available from: <https://www.who.int/publications/m/item/training-curriculum-for-the-training-of-verbal-autopsy-master-trainers-and-supervisors>.
- [13] Chandramohan D, Fottrell E, Leita J, Nichols E, Clark SJ, Alsokhn C, et al. Estimating Causes of Death Where There Is No Medical Certification: Evolution and State of the Art of Verbal Autopsy. *Global Health Action*. 2021 Oct;14(sup1):1982486. <https://doi.org/10.1080/16549716.2021.1982486>.
- [14] World Health Organization. Verbal Autopsy Standards: Ascertaining and Attributing Cause of Death. World Health Organization; 2007. Available from: https://apps.who.int/iris/bitstream/handle/10665/43764/9789241547215_eng.pdf.
- [15] Gomes M, Begum R, Sati P, Dikshit R, Gupta PC, Kumar R, et al. Nationwide Mortality Studies To Quantify Causes Of Death: Relevant Lessons From India's Million Death Study. *Health Affairs*. 2017 Nov;36(11):1887–1895. <https://doi.org/10.1377/hlthaff.2017.0635>.
- [16] Jha P, Gajalakshmi V, Gupta PC, Kumar R, Mony P, Dhingra N, et al. Prospective Study of One Million Deaths in India: Rationale, Design, and Validation Results. *PLOS Medicine*. 2005 Dec;3(2):e18. <https://doi.org/10.1371/journal.pmed.0030018>.
- [17] McCormick TH, Li ZR, Calvert C, Crampin AC, Kahn K, Clark SJ. Probabilistic Cause-of-death Assignment Using Verbal Autopsies. *Journal of the American Statistical Association*. 2016;111(515):1036–1049. <https://doi.org/10.1080/01621459.2016.1152191>.
- [18] Morris SK, Bassani DG, Kumar R, Awasthi S, Paul VK, Jha P. Factors Associated with Physician Agreement on Verbal Autopsy of over 27000 Childhood Deaths in India. *PloS one*. 2010;5(3):e9583.
- [19] Soleman N, Chandramohan D, Shibuya K. Verbal Autopsy: Current Practices and Challenges. *Bulletin of the World Health Organization*. 2006;84(3):239–245.
- [20] Byass P, Hussain-Alkhateeb L, D'Ambruoso L, Clark S, Davies J, Fottrell E, et al. An Integrated Approach to Processing WHO-2016 Verbal Autopsy Data: The InterVA-5 Model. *BMC Medicine*. 2019 May;17(1):102. <https://doi.org/10.1186/s12916-019-1333-6>.

- [21] Jha P, Kumar D, Dikshit R, Budukh A, Begum R, Sati P, et al. Automated versus Physician Assignment of Cause of Death for Verbal Autopsies: Randomized Trial of 9374 Deaths in 117 Villages in India. *BMC Medicine*. 2019 Jun;17(1):116. <https://doi.org/10.1186/s12916-019-1353-2>.
- [22] Leitao J, Desai N, Aleksandrowicz L, Byass P, Miasnikof P, Tollman S, et al. Comparison of Physician-Certified Verbal Autopsy with Computer-Coded Verbal Autopsy for Cause of Death Assignment in Hospitalized Patients in Low- and Middle-Income Countries: Systematic Review. *BMC Medicine*. 2014 Feb;12(1):22. <https://doi.org/10.1186/1741-7015-12-22>.
- [23] Desai N, Aleksandrowicz L, Miasnikof P, Lu Y, Leitao J, Byass P, et al. Performance of Four Computer-Coded Verbal Autopsy Methods for Cause of Death Assignment Compared with Physician Coding on 24,000 Deaths in Low- and Middle-Income Countries. *BMC Medicine*. 2014 Feb;12(1):20. <https://doi.org/10.1186/1741-7015-12-20>.
- [24] Tunga M, Lungo J, Chambua J, Kateule R. Verbal Autopsy Models in Determining Causes of Death. *Tropical Medicine & International Health*. 2021;26(12):1560–1567. <https://doi.org/10.1111/tmi.13678>.
- [25] Oti SO, Kyobutungi C. Verbal Autopsy Interpretation: A Comparative Analysis of the InterVA Model versus Physician Review in Determining Causes of Death in the Nairobi DSS. *Population Health Metrics*. 2010 Jun;8(1):21. <https://doi.org/10.1186/1478-7954-8-21>.
- [26] Jeblee S, Gomes M, Jha P, Rudzicz F, Hirst G. Automatically Determining Cause of Death from Verbal Autopsy Narratives. *BMC Medical Informatics and Decision Making*. 2019 Jul;19(1):127. <https://doi.org/10.1186/s12911-019-0841-9>.
- [27] Blanco A, Pérez A, Casillas A, Cobos D. Extracting Cause of Death From Verbal Autopsy With Deep Learning Interpretable Methods. *IEEE Journal of Biomedical and Health Informatics*. 2021 Apr;25(4):1315–1325. <https://doi.org/10.1109/JBHI.2020.3005769>.
- [28] King C, Zamawe C, Banda M, Bar-Zeev N, Beard J, Bird J, et al. The Quality and Diagnostic Value of Open Narratives in Verbal Autopsy: A Mixed-Methods Analysis of Partnered Interviews from Malawi. *BMC Medical Research Methodology*. 2016 Feb;16(1):13. <https://doi.org/10.1186/s12874-016-0115-5>.
- [29] Chang Y, Wang X, Wang J, Wu Y, Yang L, Zhu K, et al.: A Survey on Evaluation of Large Language Models. *arXiv*. Available from: <http://arxiv.org/abs/2307.03109>.
- [30] Lund BD, Wang T. Chatting about ChatGPT: How May AI and GPT Impact Academia and Libraries? *Library Hi Tech News*. 2023 Jan;40(3):26–29. <https://doi.org/10.1108/LHTN-01-2023-0009>.

- [31] Svyatkovskiy A, Deng SK, Fu S, Sundaresan N. IntelliCode Compose: Code Generation Using Transformer. In: Proceedings of the 28th ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering. ESEC/FSE 2020. New York, NY, USA: Association for Computing Machinery; 2020. p. 1433–1443. Available from: <https://doi.org/10.1145/3368089.3417058>.
- [32] Haupt CE, Marks M. AI-Generated Medical Advice—GPT and Beyond. JAMA. 2023 Apr;329(16):1349–1350. <https://doi.org/10.1001/jama.2023.5321>.
- [33] Wu T, He S, Liu J, Sun S, Liu K, Han QL, et al. A Brief Overview of ChatGPT: The History, Status Quo and Potential Future Development. IEEE/CAA Journal of Automatica Sinica. 2023;10(5):1122–1136. <https://doi.org/10.1109/JAS.2023.123618>.
- [34] Njala University.: Healthy Sierra Leone. Available from: <https://healsl.org/>.
- [35] Carshon-Marsh R, Aimone A, Ansumana R, Swaray IB, Assalif A, Musa A, et al. Child, Maternal, and Adult Mortality in Sierra Leone: Nationally Representative Mortality Survey 2018–20. The Lancet Global Health. 2022 Jan;10(1):e114–e123. [https://doi.org/10.1016/S2214-109X\(21\)00459-9](https://doi.org/10.1016/S2214-109X(21)00459-9).
- [36] World Health Organization. ICD-10: International Statistical Classification of Diseases and Related Health Problems (10th Revision); 2011.
- [37] Aleksandrowicz L, Malhotra V, Dikshit R, Gupta PC, Kumar R, Sheth J, et al. Performance Criteria for Verbal Autopsy-Based Systems to Estimate National Causes of Death: Development and Application to the Indian Million Death Study. BMC Medicine. 2014 Feb;12(1):21. <https://doi.org/10.1186/1741-7015-12-21>.
- [38] Barnett ML, Boddupalli D, Nundy S, Bates DW. Comparative Accuracy of Diagnosis by Collective Intelligence of Multiple Physicians vs Individual Physicians. JAMA Network Open. 2019 Mar;2(3):e190096. <https://doi.org/10.1001/jamanetworkopen.2019.0096>.
- [39] Hsiao M, Morris SK, Bassani DG, Montgomery AL, Thakur JS, Jha P. Factors Associated with Physician Agreement on Verbal Autopsy of over 11500 Injury Deaths in India. PLOS ONE. 2012 Jan;7(1):e30336. <https://doi.org/10.1371/journal.pone.0030336>.
- [40] Brown TB, Mann B, Ryder N, Subbiah M, Kaplan J, Dhariwal P, et al.: Language Models Are Few-Shot Learners. arXiv. Available from: <http://arxiv.org/abs/2005.14165>.

- [41] Vaswani A, Shazeer N, Parmar N, Uszkoreit J, Jones L, Gomez AN, et al. Attention Is All You Need. In: *Advances in Neural Information Processing Systems*. vol. 30. Curran Associates, Inc.; 2017. Available from: https://papers.nips.cc/paper_files/paper/2017/hash/3f5ee243547dee91fbd053c1c4a845aa-Abstract.html.
- [42] Ouyang L, Wu J, Jiang X, Almeida D, Wainwright CL, Mishkin P, et al.: Training Language Models to Follow Instructions with Human Feedback. *arXiv*. Available from: <http://arxiv.org/abs/2203.02155>.
- [43] Christiano PF, Leike J, Brown T, Martic M, Legg S, Amodei D. Deep Reinforcement Learning from Human Preferences. *Advances in neural information processing systems*. 2017;30.
- [44] Stiennon N, Ouyang L, Wu J, Ziegler D, Lowe R, Voss C, et al. Learning to Summarize with Human Feedback. *Advances in Neural Information Processing Systems*. 2020;33:3008–3021.
- [45] Wirth C, Akrou R, Neumann G, Fürnkranz J. A Survey of Preference-Based Reinforcement Learning Methods. *The Journal of Machine Learning Research*. 2017 Jan;18(1):4945–4990.
- [46] Murray CJ, Lozano R, Flaxman AD, Serina P, Phillips D, Stewart A, et al. Using Verbal Autopsy to Measure Causes of Death: The Comparative Performance of Existing Methods. *BMC Medicine*. 2014 Jan;12(1):5. <https://doi.org/10.1186/1741-7015-12-5>.
- [47] Benara SK, Sharma S, Juneja A, Nair S, Gulati BK, Singh KJ, et al. Evaluation of Methods for Assigning Causes of Death from Verbal Autopsies in India. *Frontiers in Big Data*. 2023 Aug;6:1197471. <https://doi.org/10.3389/fdata.2023.1197471>.
- [48] Li ZR, Thomas J, Choi E, McCormick TH, Clark SJ. The openVA Toolkit for Verbal Autopsies. *The R Journal*. 2023 Feb;p. 1.
- [49] BAYES. An Essay towards Solving a Problem in the Doctrine of Chances. *Biometrika*. 1958;45(3-4):296–315.
- [50] Byass P, Chandramohan D, Clark SJ, D’Ambruoso L, Fottrell E, Graham WJ, et al. Strengthening Standardised Interpretation of Verbal Autopsy Data: The New InterVA-4 Tool. *Global Health Action*. 2012 Dec;5(1):19281. <https://doi.org/10.3402/gha.v5i0.19281>.
- [51] Brooks S. Markov Chain Monte Carlo Method and Its Application. *Journal of the Royal Statistical Society: Series D (The Statistician)*. 1998 Mar;47(1):69–100. <https://doi.org/10.1111/1467-9884.00117>.

- [52] Chib S. Markov Chain Monte Carlo Methods: Computation and Inference. Handbook of econometrics. 2001;5:3569–3649.
- [53] Han C, Carlin BP. Markov Chain Monte Carlo Methods for Computing Bayes Factors: A Comparative Review. Journal of the American Statistical Association. 2001 Sep;96(455):1122–1132. <https://doi.org/10.1198/016214501753208780>.
- [54] World Health Organization.: ODK for Verbal Autopsy: A Quick Guide. Available from: <https://www.who.int/publications/m/item/odk-for-verbal-autopsy--a-quick-guide>.
- [55] Nafundi.: ODK - Collect Data Anywhere. Available from: <https://getodk.org>.
- [56] DiPasquale A, Maire N, Bratschi M.: Release ODK 2016 WHO VA Instrument 1.5.1 SwissTPH/WHO-VA. Swiss Tropical and Public Health Institute. Available from: <https://github.com/SwissTPH/WHO-VA/releases/tag/1.5%2C1>.
- [57] Byass P.: InterVA-5.1 User Guide. Available from: <http://www.byass.uk/interva/products>.
- [58] Thomas J, ekarpinskiMITRE, pkmitre, owentrigueros, Choi P, Chu Y.: Pycrossva: Prepare Data from WHO and PHRMC Instruments for Verbal Autopsy Algorithms. Available from: <https://pypi.org/project/pycrossva/>.
- [59] OpenAI.: OpenAI Platform: API Reference (Temperature Parameter). Available from: <https://platform.openai.com/docs/api-reference/completions/create#completions-create-temperature>.
- [60] Li ZR, McCormick T, Clark S.: InSilicoVA: Probabilistic Verbal Autopsy Coding with 'InSilicoVA' Algorithm. Available from: <https://cran.r-project.org/package=InSilicoVA>.
- [61] Thomas J, Li Z, Byass P, McCormick T, Boyas M, Clark S.: InterVA5: Replicate and Analyse 'InterVA5'. Available from: <https://cran.r-project.org/package=InterVA5>.
- [62] Yendewa GA, Poveda E, Yendewa SA, Sahr F, Quiñones-Mateu ME, Salata RA. HIV/AIDS in Sierra Leone: Characterizing the Hidden Epidemic. AIDS reviews. 2018;20(2).
- [63] Walker PG, White MT, Griffin JT, Reynolds A, Ferguson NM, Ghani AC. Malaria Morbidity and Mortality in Ebola-affected Countries Caused by Decreased Health-Care Capacity, and the Potential Effect of Mitigation Strategies: A Modelling Analysis. The Lancet Infectious Diseases. 2015;15(7):825–832.
- [64] World Health Organization.: Verbal Autopsy Standards: The 2016 WHO Verbal Autopsy Instrument. Available from: <https://www.who.int/publications/m/>

[item/verbal-autopsy-standards-the-2016-who-verbal-autopsy-instrument.](#)

- [65] Murray CJ, Lozano R, Flaxman AD, Vahdatpour A, Lopez AD. Robust Metrics for Assessing the Performance of Different Verbal Autopsy Cause Assignment Methods in Validation Studies. *Population Health Metrics*. 2011 Aug;9(1):28. <https://doi.org/10.1186/1478-7954-9-28>.
- [66] Setel PW, Whiting DR, Hemed Y, Chandramohan D, Wolfson LJ, Alberti KGMM, et al. Validity of Verbal Autopsy Procedures for Determining Cause of Death in Tanzania. *Tropical Medicine & International Health*. 2006;11(5):681–696. <https://doi.org/10.1111/j.1365-3156.2006.01603.x>.
- [67] OpenAI.: Pricing. Available from: <https://openai.com/api/pricing/>.
- [68] Tao G, Cheng S, Zhang Z, Zhu J, Shen G, Zhang X.: Opening A Pandora’s Box: Things You Should Know in the Era of Custom GPTs. *arXiv*. Available from: <http://arxiv.org/abs/2401.00905>.
- [69] Khowaja SA, Khuwaja P, Dev K, Wang W, Nkenyereye L. ChatGPT Needs SPADE (Sustainability, PrivAcy, Digital Divide, and Ethics) Evaluation: A Review. *Cognitive Computation*. 2024 May;<https://doi.org/10.1007/s12559-024-10285-1>.
- [70] Wu X, Duan R, Ni J. Unveiling Security, Privacy, and Ethical Concerns of ChatGPT. *Journal of Information and Intelligence*. 2024;2(2):102–115.
- [71] Johnson D, Goodman R, Patrinely J, Stone C, Zimmerman E, Donald R, et al. Assessing the Accuracy and Reliability of AI-Generated Medical Responses: An Evaluation of the Chat-GPT Model. *Research Square*. 2023 Feb;p. rs.3.rs-2566942. <https://doi.org/10.21203/rs.3.rs-2566942/v1>.
- [72] Jang ME, Lukasiewicz T.: Consistency Analysis of ChatGPT. *arXiv*. Available from: <http://arxiv.org/abs/2303.06273>.
- [73] Krishna S, Bhambra N, Bleakney R, Bhayana R, Atzen S. Evaluation of Reliability, Repeatability, Robustness, and Confidence of GPT-3.5 and GPT-4 on a Radiology Board-Style Examination. *Radiology*. 2024 May;311(2):e232715. <https://doi.org/10.1148/radiol.232715>.
- [74] Wang J, Shi E, Yu S, Wu Z, Ma C, Dai H, et al.: Prompt Engineering for Healthcare: Methodologies and Applications. *arXiv*. Available from: <http://arxiv.org/abs/2304.14670>.
- [75] Meskó B. Prompt Engineering as an Important Emerging Skill for Medical Professionals: Tutorial. *Journal of medical Internet research*. 2023;25:e50638.

- [76] Almasre M. Development and Evaluation of a Custom GPT for the Assessment of Students' Designs in a Typography Course. *Education Sciences*. 2024 Feb;14(2):148. <https://doi.org/10.3390/educsci14020148>.