

Title: Learning Bundled Care Opportunities from Electronic Medical Records

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Appendix A Survey Questions

The four survey questions are shown in Table A1. Each question is accompanied by a pair of (inferred, random) clusters of health conditions. The inferred cluster was learned by our framework. The other was randomly generated, but constrained to consist of the same number of PheWAS codes as the inferred cluster. The survey respondents were not provided with any indication of which cluster was inferred by our framework and which was randomly generated.

Table A1 Each survey question contains one inferred cluster and one random cluster of the same size.

Question 1: To what extent do you believe health conditions in the displayed group can be managed in a bundled manner? There are two separate groups and we ask that you evaluate each one independently of the other.	
<p>Obstetrical/birth trauma</p> <p>Late pregnancy and failed induction</p> <p>Other conditions of the mother complicating pregnancy</p> <p>Short gestation; low birth weight; and fetal growth retardation</p> <p>Other perinatal conditions</p> <p>Perinatal jaundice/isoimmunization</p> <p>Skull fracture and other intracranial injury</p> <p>Internal injury to organs</p> <p><input type="checkbox"/> Not at all likely</p> <p><input type="checkbox"/> Slightly likely</p> <p><input type="checkbox"/> Moderately likely</p> <p><input type="checkbox"/> Very likely</p> <p><input type="checkbox"/> Completely likely</p>	<p>Fever of unknown origin</p> <p>Diarrhea</p> <p>Chemotherapy</p> <p>Pancytopenia</p> <p>Gastroesophageal reflux disease</p> <p>Essential hypertension</p> <p>Asthma</p> <p>Coronary atherosclerosis</p> <p><input type="checkbox"/> Not at all likely</p> <p><input type="checkbox"/> Slightly likely</p> <p><input type="checkbox"/> Moderately likely</p> <p><input type="checkbox"/> Very likely</p> <p><input type="checkbox"/> Completely likely</p>

Question 2: To what extent do you believe health conditions in the displayed group can be managed in a bundled manner? There are two separate groups and we ask that you evaluate each one independently of the other.

Hypothyroidism

Anemia NOS

Hypopotassemia

Problems associated with amniotic cavity and membranes

Systolic/diastolic heart failure

Prostate cancer

Other abnormal glucose

- Not at all likely
- Slightly likely
- Moderately likely
- Very likely
- Completely likely

Obstetrical/birth trauma

Umbilical cord complications during labor and delivery

Other conditions of the mother complicating pregnancy

Malposition and malpresentation of fetus or obstruction

Problems associated with amniotic cavity and membranes

Abnormality pelvic soft tissues & organs complicating pregnancy

Indications for care or intervention related to labor and delivery NEC

- Not at all likely
- Slightly likely
- Moderately likely
- Very likely
- Completely likely

Question 3: To what extent do you believe health conditions in the displayed group can be managed in a bundled manner? There are two separate groups and we ask that you evaluate each one independently of the other.

Hyperlipidemia

Essential hypertension

Hyperplasia of prostate

Anemia NOS

Gastroesophageal Reflux Disease

Osteoarthritis; localized

Obstructive sleep apnea

Asthma

Hypothyroidism

Hypopotassemia

- Not at all likely
- Slightly likely
- Moderately likely
- Very likely
- Completely likely

Diarrhea

Osteoarthritis; localized

Hyperplasia of prostate

Transient cerebral ischemia

Late effects of cerebrovascular disease

Abnormality pelvic soft tissues & organs complicating pregnancy

Hypertensive chronic kidney disease

Pneumonia

Atrial fibrillation

Sepsis

- Not at all likely
- Slightly likely
- Moderately likely
- Very likely
- Completely likely

Question 4: To what extent do you believe health conditions in the displayed group can be managed in a bundled manner? There are two separate groups and we ask that you evaluate each one independently of the other.

Atrial fibrillation
 Systolic/diastolic heart failure
 Heart failure
 Venous embolism & thrombosis
 Hemorrhagic disorder due to intrinsic circulating anticoagulants
 Hypertensive chronic kidney disease
 Chronic renal failure
 Depression
 Urinary tract infection
 Decubitus ulcer
 Type 2 diabetes
 Hyperlipidemia
 Essential hypertension
 Substance addiction and disorders
 Tobacco use disorder
 Transient cerebral ischemia

- Not at all likely
- Slightly likely
- Moderately likely
- Very likely
- Completely likely

Skull fracture and other intracranial injury
 Internal injury to organs
 Hypothyroidism
 Anemia
 Hypopotassemia
 Diarrhea
 Chemotherapy
 Hyperlipidemia
 Essential hypertension
 Hyperplasia of prostate
 Chronic airway obstruction
 Malposition and malpresentation of fetus or obstruction
 Problems associated with amniotic cavity and membranes
 Gastroesophageal reflux disease
 Liver abscess and sequelae of chronic liver disease
 Multiple gestation

- Not at all likely
- Slightly likely
- Moderately likely
- Very likely
- Completely likely

Appendix B: Workflow Topics

As noted in the main manuscript, the framework discovered 25 workflows topics. Each workflow topic consists of the top 10 subsequences with the highest probability for that topic.

We visualized each workflow as a process graph via Business Process Model and Notation (BPMN) in ProM. There are six symbols within a graph, which are introduced as:

Rounded rectangle: An event.

Green circle: A start state.

Red circle: A completed state.

Right arrow: A transition process.

A pair of crosses: A loop for all events within.

Small circle: A temporal state.

Workflow w₁

Patient Care Staff Nurse (Pilot) -> Medical Records	0.04726
Medical Records -> Patient Care Staff Nurse (Pilot)	0.04403
Patient Care Staff Nurse (Pilot) -> Medical Records -> Patient Care Staff Nurse (Pilot)	0.03230
Medical Records -> Patient Care Staff Nurse (Pilot) -> Medical Records	0.03119
Patient Care Staff Nurse (Pilot) -> Medical Records -> Patient Care Staff Nurse (Pilot) -> Medical Records	0.03077
RAD - Technologist -> ED NMH Physician-CPOE	0.01903
Patient Care Staff Nurse -> View Only PC 3	0.01491
View Only PC 3 -> Patient Care Staff Nurse	0.01353
Patient Care Staff Nurse -> View Only PC 3 -> Patient Care Staff Nurse	0.01300
Rehab OT -> Medical Records	0.01110

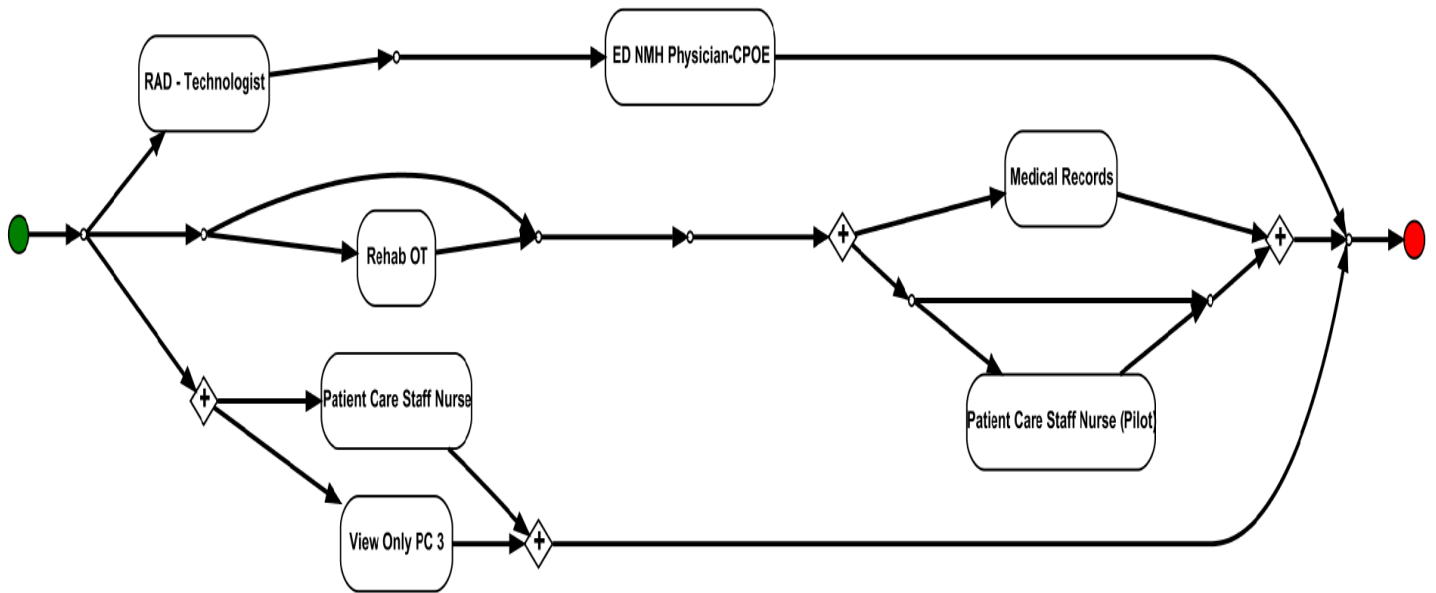


Figure A1 Process graph of workflow w₁

Workflow w_2

NMH Physician Office - CPOE -> Utilization Review (UR)/ Quality Assurance (QA)	0.02523
UR/ QA -> NMH Physician Office - CPOE	0.02296
Dietary 1 -> Medical Records	0.01846
UR/QA -> NMH Physician Office - CPOE -> UR/QA	0.01676
NMH Resident/Fellow-CPOE -> RAD - Nurse	0.01657
NMH Physician Office - CPOE -> UR/QA 1 -> NMH Physician Office - CPOE	0.01652
RAD - Nurse -> NMH Resident/Fellow-CPOE	0.01628
Medical Records -> Dietary 1	0.01519
NMH Resident/Fellow-CPOE -> RAD - Nurse -> NMH Resident/Fellow-CPOE	0.01278
Clinical Documentation Consultant -> NMH Resident/Fellow-CPOE	0.01174

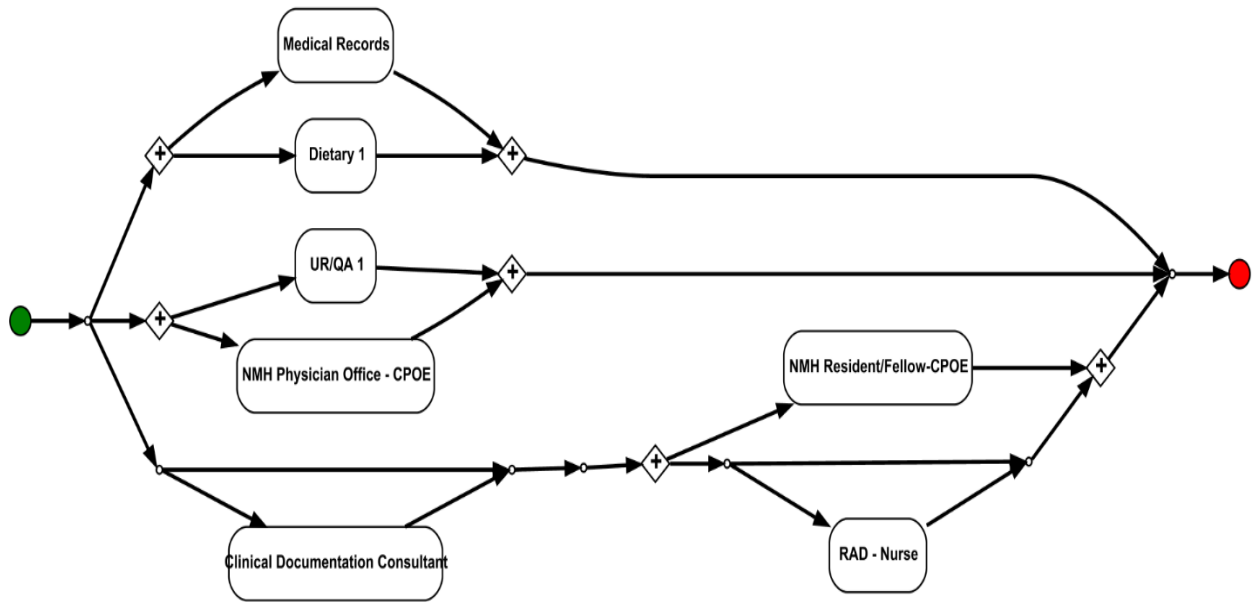


Figure A2 Process graph of workflow w_2

Workflow w_3

NMPG MD - CPOE -> Patient Care Assistive Staff	0.01895
Patient Care Assistive Staff -> NMPG MD - CPOE	0.01771
NMPG MD - CPOE -> NMPG MD - CPOE	0.01591
NMPG MD - CPOE -> NMPG MD - CPOE -> Patient Care Assistive Staff	0.01329
NMPG MD - CPOE -> Patient Care Assistive Staff -> NMPG MD - CPOE	0.01310
Patient Care Assistive Staff -> NMPG MD - CPOE -> Patient Care Assistive Staff	0.01299
Patient Care Assistive Staff -> NMPG MD - CPOE -> NMPG MD - CPOE	0.01284
NMPG MD - CPOE -> NMPG MD - CPOE -> Patient Care Assistive Staff -> NMPG MD - CPOE -> Patient Care Assistive Staff	0.01266
NMPG MD - CPOE -> Patient Care Assistive Staff -> NMPG MD - CPOE -> NMPG MD - CPOE	0.01266
NMPG MD - CPOE -> NMPG MD - CPOE -> Patient Care Assistive Staff -> NMPG MD - CPOE	0.01262

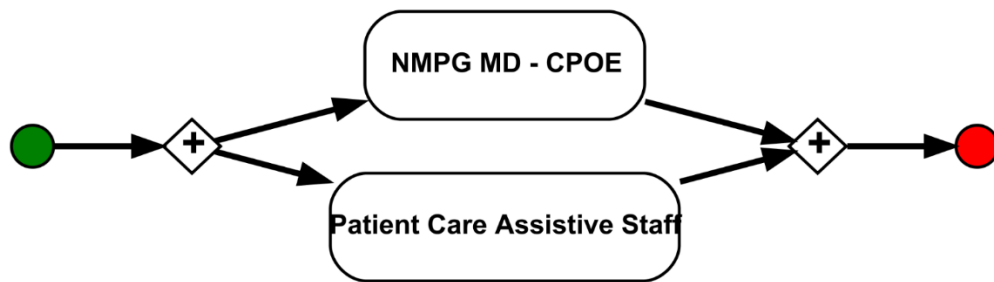


Figure A3 Process graph of workflow w_3

Workflow w₄

Unit Secretary 2 -> Patient Care Staff Nurse (Pilot)	0.02053
Patient Care Staff Nurse (Pilot) -> Unit Secretary 2	0.01752
RAD - Resident/Fellow -> Respiratory	0.01328
Patient Care Staff Nurse (Pilot) -> Unit Secretary 2 -> Patient Care Staff Nurse (Pilot)	0.01321
Patient Care Staff Nurse (Pilot) -> Unit Secretary 2 -> Unit Secretary 2	0.01304
Unit Secretary 2 -> Unit Secretary 2 -> Patient Care Staff Nurse (Pilot)	0.01297
Unit Secretary 2 -> Patient Care Staff Nurse (Pilot) -> Unit Secretary 2	0.01290
Respiratory -> RAD - Resident/Fellow	0.01225
Physician Office -> Health Information Audit-Consultant	0.00982
Health Information Audit-Consultant -> Physician Office	0.00962

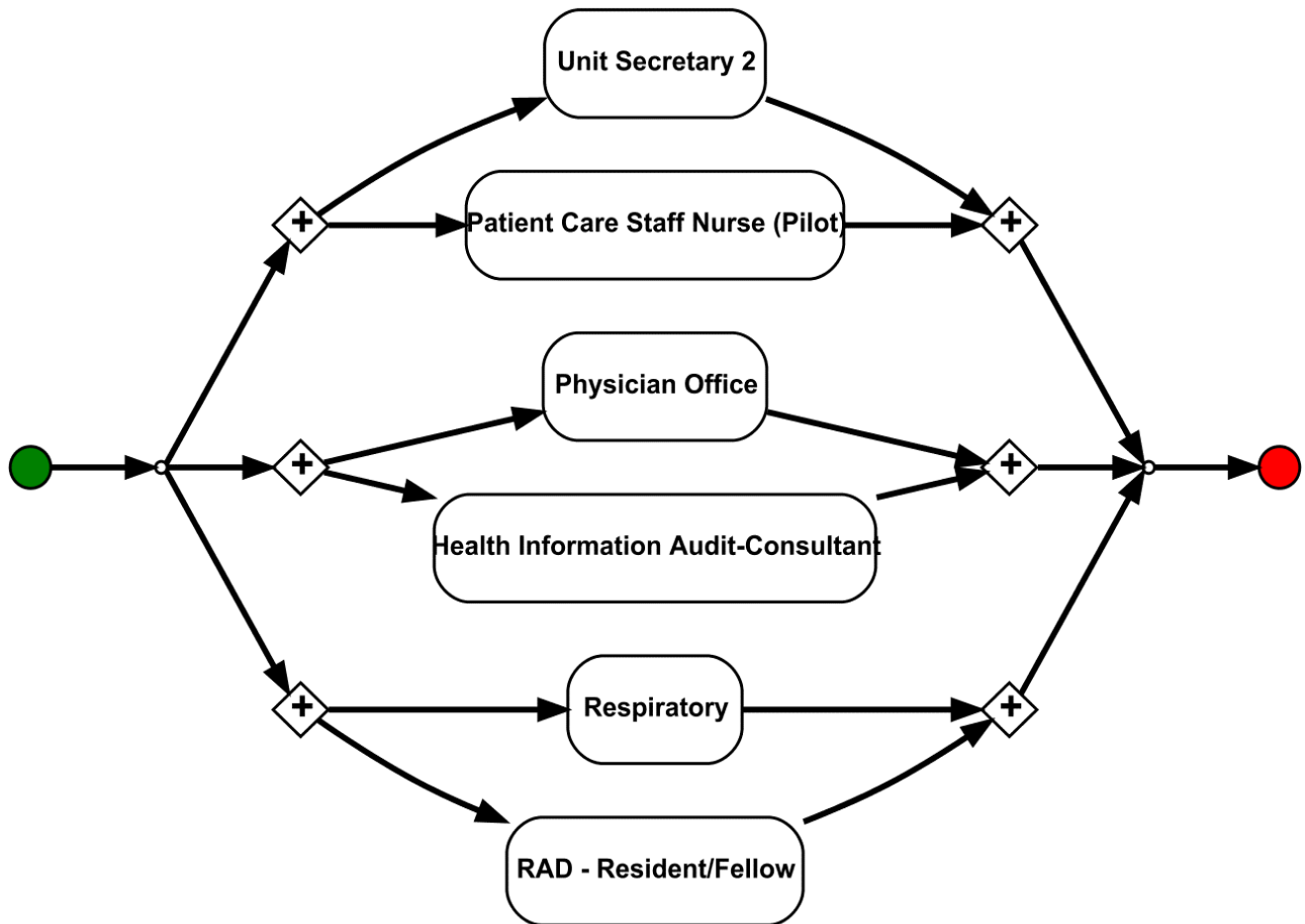


Figure A4 Process graph of workflow w₄

Workflow w₅

Student Nurse -> UR/QA 1	0.01501
RAD - Mgr/RC -> UR/QA 1	0.01470
UR/QA 1 -> RAD - Mgr/RC	0.01389
Student Nurse -> RX-Pharmacist	0.01331
RX-Pharmacist -> Student Nurse	0.01322
Patient Care Assistive Staff -> View Only PC 1	0.01273
View Only PC 1 -> Patient Care Assistive Staff	0.01264
UR/QA 1 -> Student Nurse	0.01260
UR/QA 1 -> RAD - Mgr/RC -> UR/QA 1	0.00996
UR/QA 1 -> RAD - Mgr/RC -> RAD - Mgr/RC	0.00992

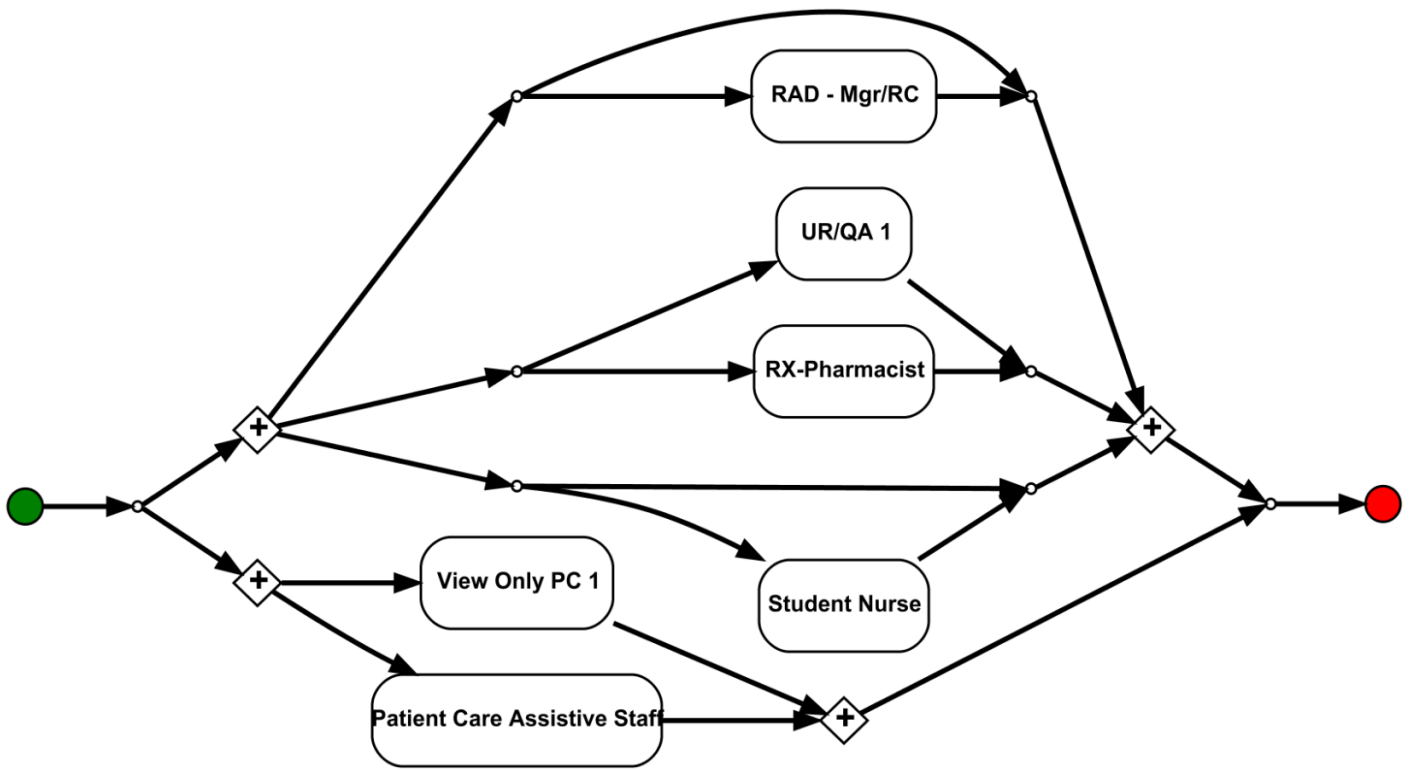


Figure A5 Process graph of workflow w₅

Workflow w₆

RAD - Technologist -> Med Student-CPOE	0.01635
Med Student-CPOE -> RAD - Technologist	0.01577
NMH Physician Hospitalist-CPOE -> Rehab PT	0.01437
NMH Resident/Fellow-CPOE -> MLPN-Medicating Licensed Practical Nurse	0.01421
MLPN-Medicating Licensed Practical Nurse -> NMH Resident/Fellow-CPOE	0.01378
Rehab PT -> NMH Physician Hospitalist-CPOE	0.01308
RAD - Resident/Fellow -> RX-Pharmacist	0.01191
Med Student-CPOE -> ED NMH Physician-CPOE	0.01168
Patient Care Staff Nurse -> PICC Nurse	0.01125
ED NMH Physician-CPOE -> Med Student-CPOE	0.01106

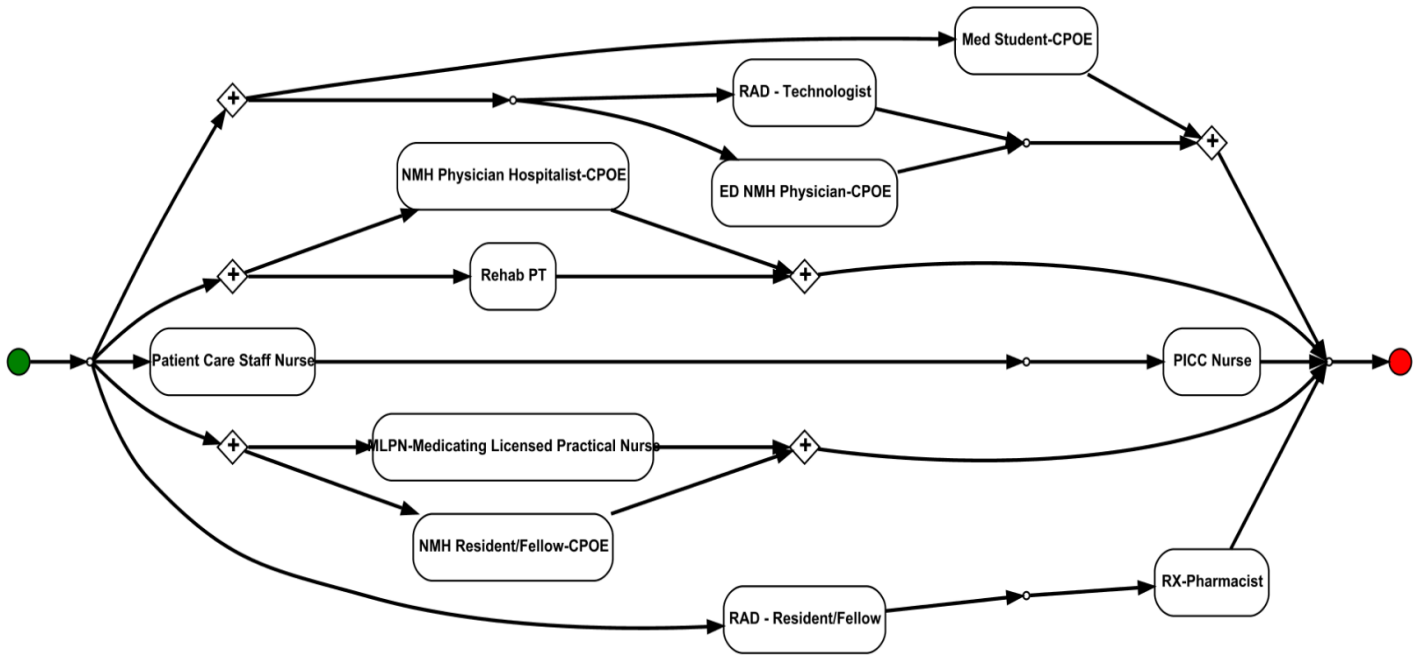


Figure A6 Process graph of workflow w₆

Workflow w₇

NMH Physician Hospitalist-CPOE -> Medical Records	0.01850
Medical Records -> NMH Physician Hospitalist-CPOE	0.01693
Student Nurse -> Respiratory	0.01606
Respiratory -> Student Nurse	0.01559
Health Information Audit-Consultant -> Medical Records	0.01296
Medical Records -> NMH Physician Hospitalist-CPOE -> Medical Records	0.01222
ED NMH Physician-CPOE -> NMH Physician Hospitalist-CPOE	0.01214
NMH Physician Hospitalist-CPOE -> Medical Records -> NMH Physician Hospitalist-CPOE	0.01210
NMH Physician Hospitalist-CPOE -> Medical Records -> NMH Physician Hospitalist-CPOE -> Medical Records	0.01206
Medical Records -> Health Information Audit-Consultant	0.01119

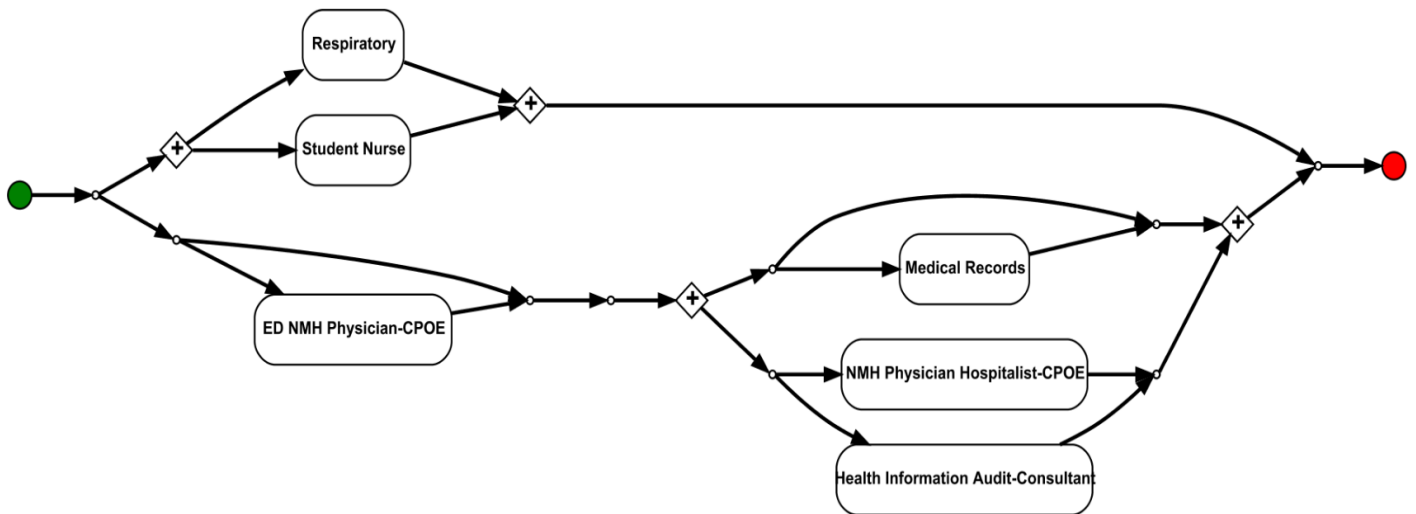


Figure A7 Process graph of workflow w₇

Workflow w₈

Medical Records - Scanner -> Physician Office	0.03089
Physician Office -> SN-RN/Customer Service	0.03023
Physician Office -> Medical Records - Scanner	0.03005
SN-RN/Customer Service -> Physician Office	0.02430
Physician Office -> Medical Records - Scanner -> Physician Office	0.02263
ED Coder -> Physician Office	0.02158
Medical Records - Scanner -> Medical Records - Scanner -> Physician Office	0.02100
Physician Office -> Medical Records - Scanner -> Medical Records - Scanner	0.02096
Medical Records - Scanner -> Physician Office -> Medical Records - Scanner	0.02093
Medical Records - Scanner -> Physician Office -> Medical Records - Scanner -> Physician Office	0.02071

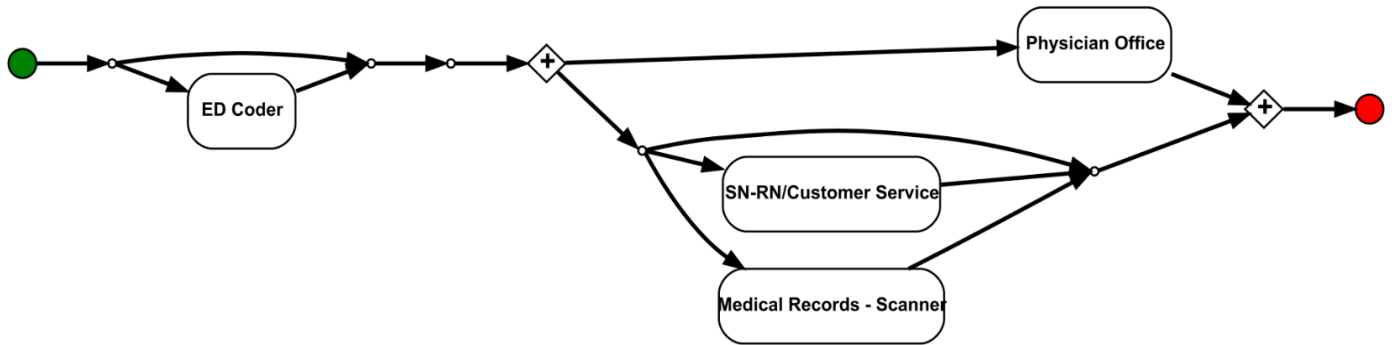


Figure A8 Process graph of workflow w₈

Workflow w₉

RAD - Technologist -> ED Unit Secretary	0.01784
ED Unit Secretary -> RAD - Technologist	0.01719
NMH Resident/Fellow-CPOE -> Transfer	0.01360
Transfer -> NMH Resident/Fellow-CPOE	0.01315
Advanced Practice Clinician - CRNA -> Patient Care Staff Nurse	0.01290
RAD - Technologist -> ED Unit Secretary -> RAD - Technologist	0.01237
Patient Care Staff Nurse -> Advanced Practice Clinician - CRNA	0.01221
ED Unit Secretary -> ED Unit Secretary -> RAD - Technologist	0.01213
RAD - Technologist -> ED Unit Secretary -> ED Unit Secretary	0.01209
ED Unit Secretary -> RAD - Technologist -> ED Unit Secretary -> RAD - Technologist	0.01192

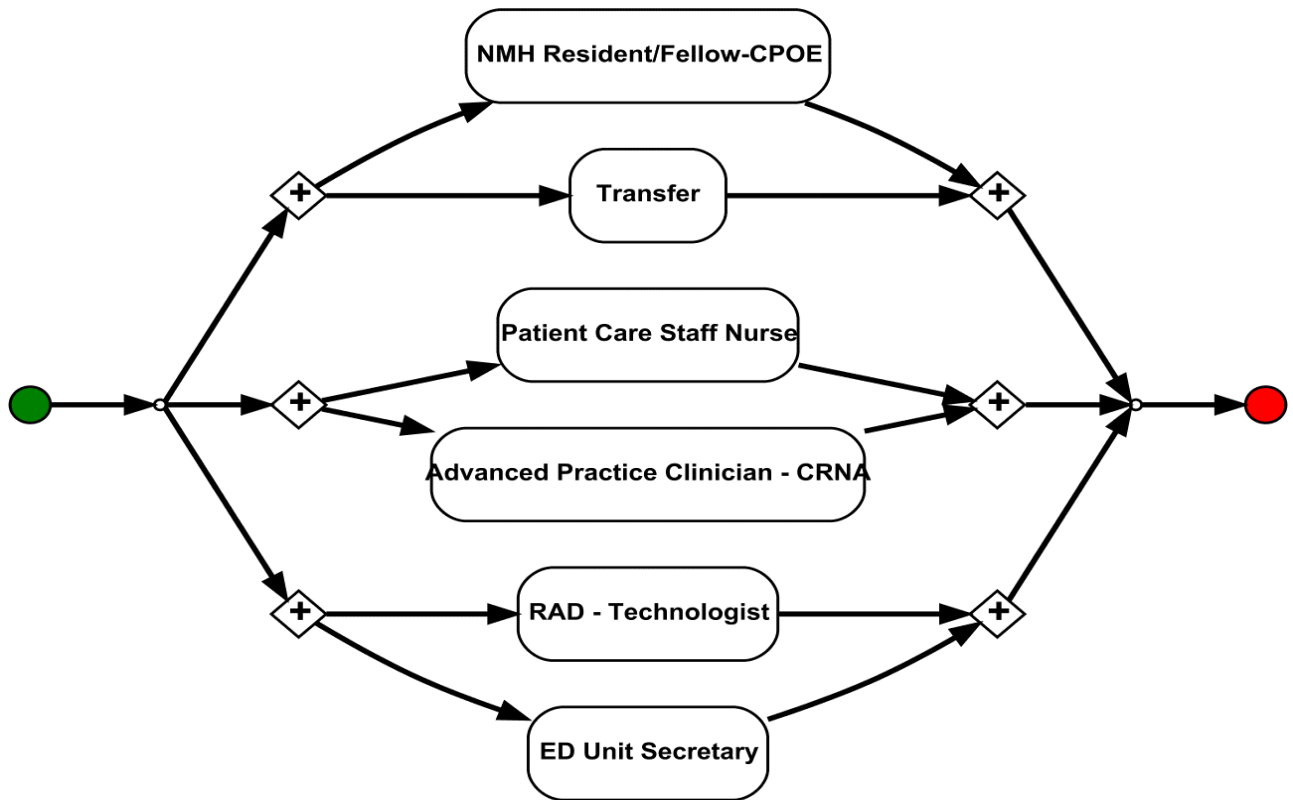


Figure A9 Process graph of workflow w₉

Workflow w₁₀

Respiratory -> ED Patient Care Staff Nurse	0.01859
ED Patient Care Staff Nurse -> Respiratory	0.01815
Patient Care Staff Nurse (Pilot) -> Advanced Practice Clinician - CPOE	0.01675
Advanced Practice Clinician - CPOE -> Patient Care Staff Nurse (Pilot)	0.01667
RAD - Resident/Fellow -> ED Patient Care Staff Nurse	0.01557
SN-RN/Customer Service -> Patient Care Staff Nurse (Pilot)	0.01483
Medical Records -> Clinical Documentation Consultant	0.01406
Patient Care Staff Nurse (Pilot) -> SN-RN/Customer Service	0.01347
Respiratory -> ED Patient Care Staff Nurse -> Respiratory	0.01302
ED Patient Care Staff Nurse -> RAD - Resident/Fellow	0.01269

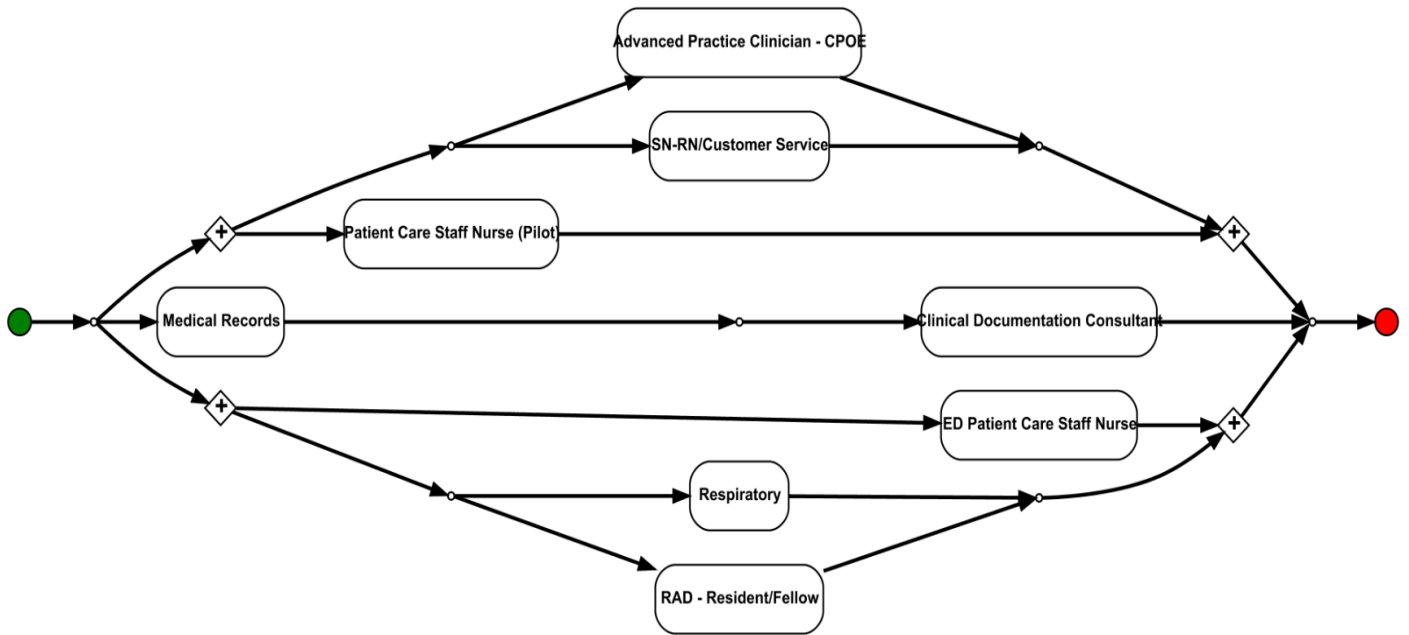


Figure A10 Process graph of workflow w₁₀

Workflow w₁₁

NMH Physician Office - CPOE -> Medical Records	0.03341
Medical Records -> NMH Physician Office - CPOE	0.02944
Advanced Practice Clinician - CPOE -> NMH Anesthesia-CPOE	0.02719
NMH Anesthesia-CPOE -> Advanced Practice Clinician - CPOE	0.02626
RX-Pharmacist -> Unit Secretary 2	0.02577
Unit Secretary 2 -> RX-Pharmacist	0.02288
NMH Physician Office - CPOE -> Medical Records -> NMH Physician Office - CPOE	0.02165
Medical Records -> NMH Physician Office - CPOE -> Medical Records	0.02131
NMH Physician Office - CPOE -> Medical Records -> NMH Physician Office - CPOE -> Medical Records	0.02116
NMH Physician Office - CPOE -> RX-Pharmacist	0.02008

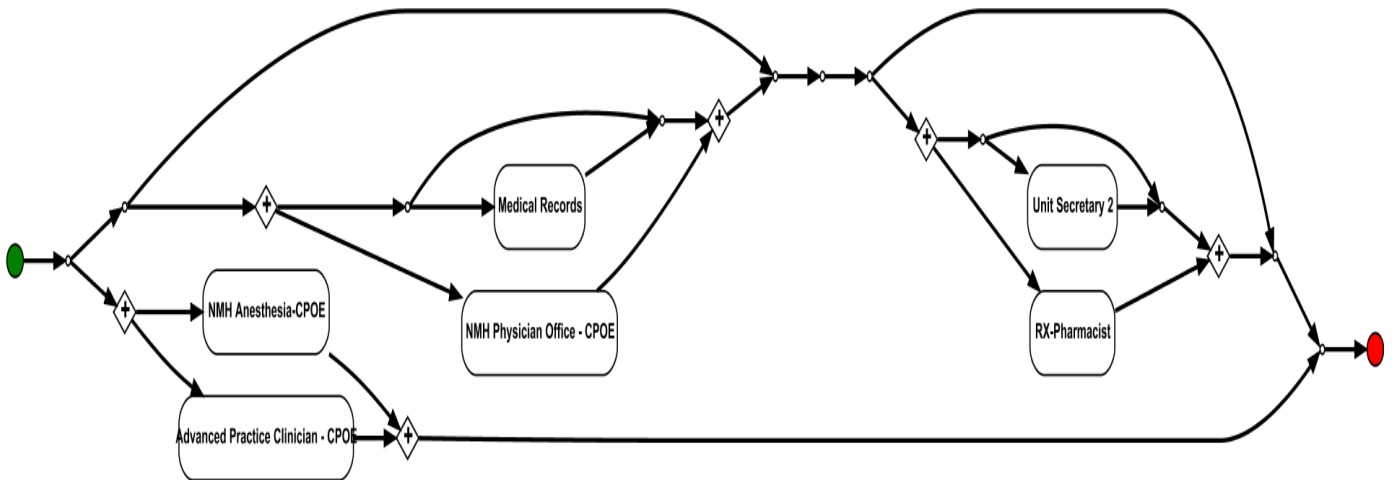


Figure A11 Process graph of workflow w₁₁

Workflow w₁₂

NMH Physician Office - CPOE -> Patient Care Staff Nurse (Pilot)	0.02177
Patient Care Staff Nurse (Pilot) -> NMH Physician Office - CPOE	0.02049
NMH Physician Office - CPOE -> Advanced Practice Clinician - CPOE	0.02002
Respiratory -> NMH Physician Office - CPOE	0.01855
Advanced Practice Clinician - CPOE -> NMH Physician Office - CPOE	0.01808
NMH Physician Office - CPOE -> Respiratory	0.01803
Patient Care Staff Nurse (Pilot) -> NMH Physician Office - CPOE -> Patient Care Staff Nurse (Pilot)	0.01533
SN-OR RN SC -> RX-Pharmacist	0.01529
NMH Resident/Fellow-CPOE -> NU Researcher	0.01486
NMH Physician Office - CPOE -> Patient Care Staff Nurse (Pilot) -> NMH Physician Office - CPOE	0.01462

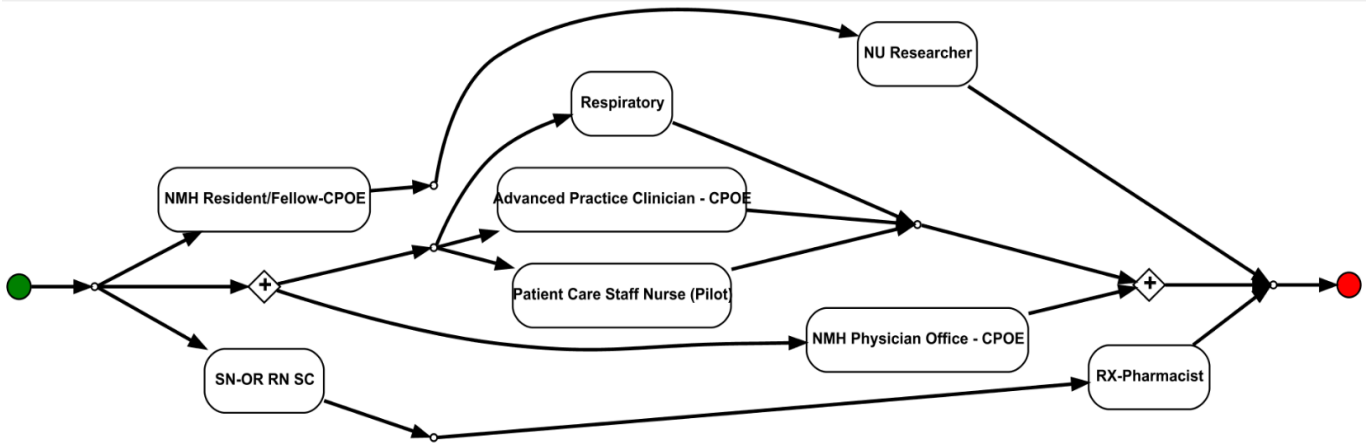


Figure A12 Process graph of workflow w₁₂

Workflow w₁₃

NMH Physician Office - CPOE -> Med Student-CPOE	0.02844
Med Student-CPOE -> NMH Physician Office - CPOE	0.02717
Unit Secretary 2 -> NMH Physician Office - CPOE	0.02425
NMH Physician Office - CPOE -> Unit Secretary 2	0.02400
Med Student-CPOE -> NMH Physician Office - CPOE -> Med Student-CPOE	0.01883
NMH Physician Office - CPOE -> Med Student-CPOE -> NMH Physician Office - CPOE	0.01878
NMH Physician Office - CPOE -> Unit Secretary 2 -> Unit Secretary 2	0.01678
Unit Secretary 2 -> NMH Physician Office - CPOE -> Unit Secretary 2	0.01673
Unit Secretary 2 -> Unit Secretary 2 -> NMH Physician Office - CPOE	0.01663
NMH Physician Office - CPOE -> Unit Secretary 2 -> NMH Physician Office - CPOE	0.01654

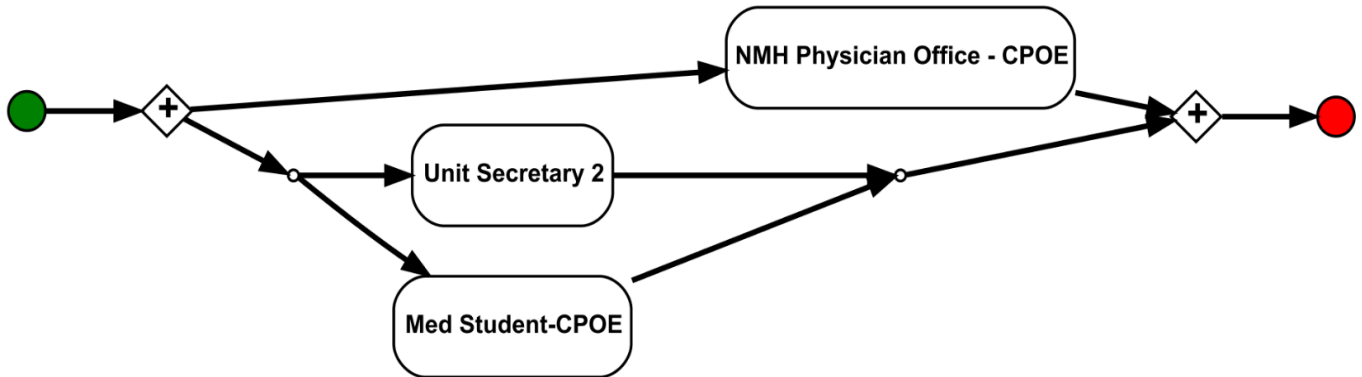


Figure A13 Process graph of workflow w₁₃

Workflow w₁₄

NMH Physician Office - CPOE -> Physician Office	0.03611
Physician Office -> NMH Physician Office - CPOE	0.03096
NMH Physician Office - CPOE -> Physician Office -> NMH Physician Office - CPOE	0.02538
Physician Office -> NMH Physician Office - CPOE -> Physician Office	0.02345
Medical Records - Scanner -> Medical Records	0.02318
NMH Physician Office - CPOE -> Physician Office -> NMH Physician Office - CPOE -> Physician Office	0.02307
NMH Physician Office - CPOE -> Physician Office -> NMH Physician Office - CPOE -> Physician Office-> Physician Office	0.02302
Patient Care Assistive Staff -> NMH Anesthesia-CPOE	0.01739
NMH Anesthesia-CPOE -> NMH Anesthesia-CPOE	0.01503
ED Patient Care Staff Nurse -> Patient Care Staff Nurse (Pilot)	0.01277

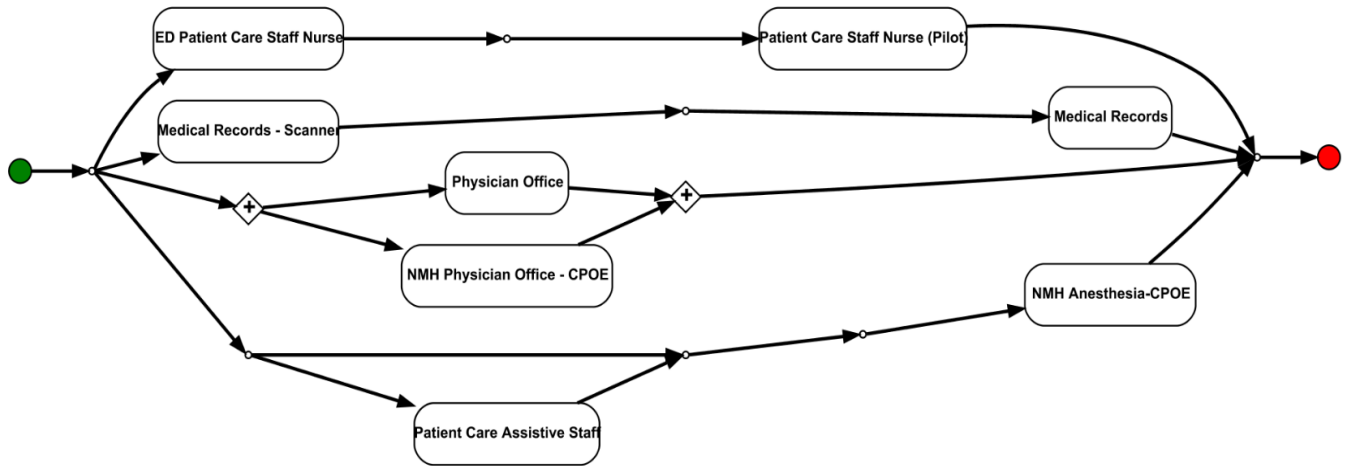


Figure A14 Process graph of workflow w₁₄

Workflow w₁₅

Attending Phys/Prov -> NMH Physician-CPOE	0.04076
NMH Physician-CPOE -> Patient Care Staff Nurse - Lactation	0.01873
RAD - Technologist -> NMH Physician Hospitalist-CPOE	0.01765
NMH Physician Hospitalist-CPOE -> RAD - Technologist	0.01726
Patient Care Staff Nurse - Lactation -> NMH Physician-CPOE	0.01711
NMH Physician-CPOE -> Patient Care Staff Nurse - Lactation -> NMH Physician-CPOE	0.01277
Patient Care Staff Nurse-Lactation -> Patient Care Staff Nurse-Lactation -> NMH Physician-CPOE	0.01250
NMH Physician-CPOE -> Patient Care Staff Nurse - Lactation -> Patient Care Staff Nurse - Lactation	0.01246
Patient Care Staff Nurse - Lactation -> NMH Physician-CPOE -> Patient Care Staff Nurse - Lactation	0.01238
Patient Care Staff Nurse - Lactation -> NMH Physician-CPOE -> Patient Care Staff Nurse - Lactation -> NMH Physician-CPOE	0.01230

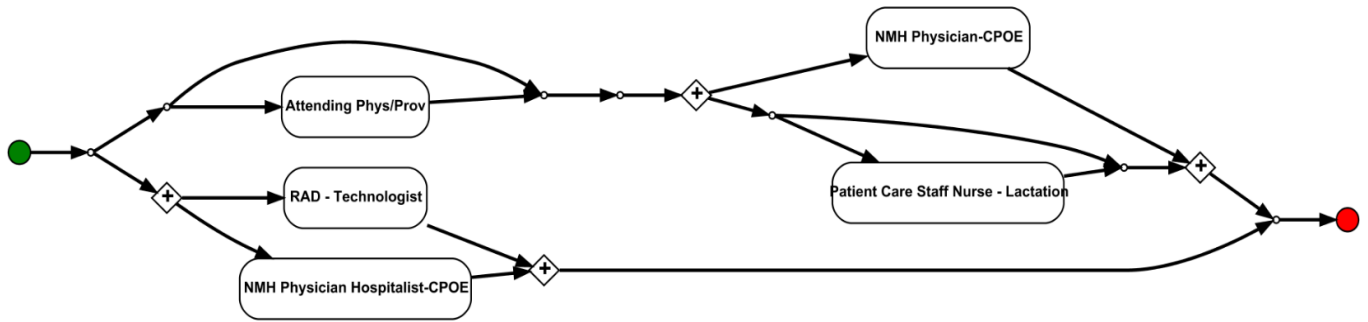


Figure A15 Process graph of workflow w₁₅

Workflow w₁₆

SN-RN/Customer Service -> UR/QA 1	0.01997
UR/QA 1 -> SN-RN/Customer Service	0.01993
RX-Pharmacist -> Rehab OT	0.01908
Rehab PT -> NMH Physician-CPOE	0.01882
Rehab OT -> RX-Pharmacist	0.01856
NMH Physician-CPOE -> Rehab PT	0.01660
Respiratory -> Dietary 2	0.01617
Dietary 2 -> Respiratory	0.01506
UR/QA 1 -> ED Registration	0.01493
SN-RN/Customer Service -> UR/QA 1 -> SN-RN/Customer Service	0.01390

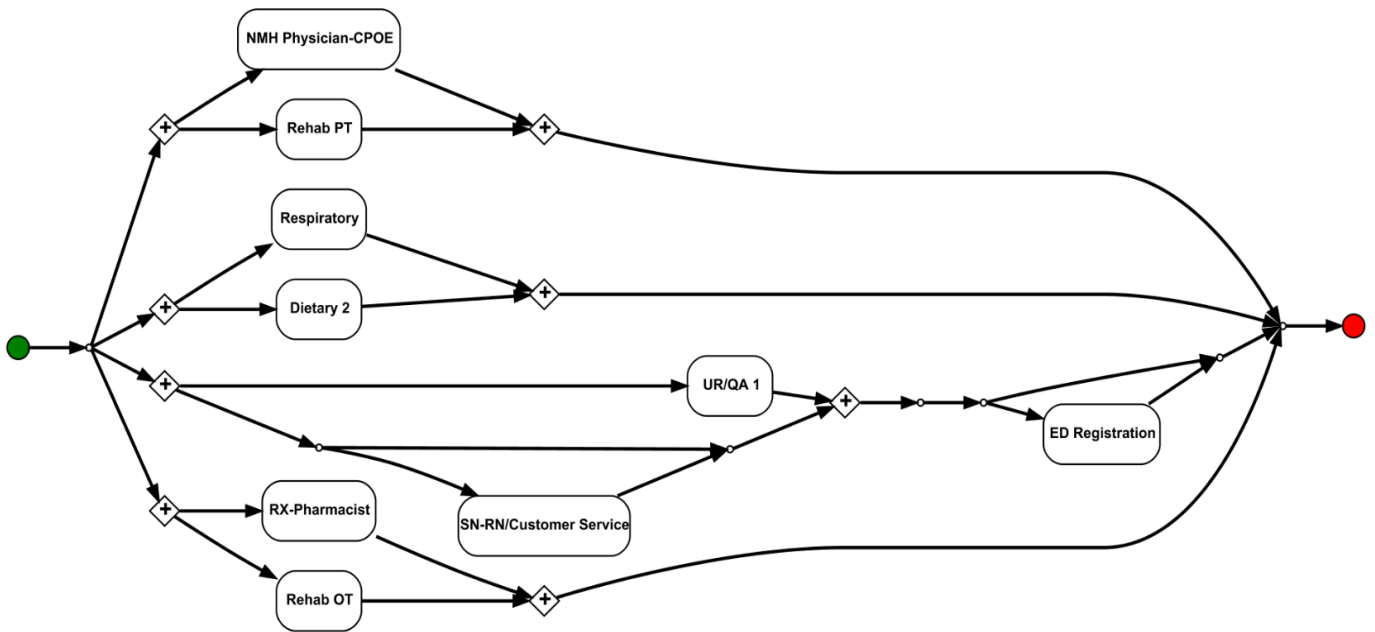


Figure A16 Process graph of workflow w₁₆

Workflow w₁₇

NMH Physician Office - CPOE -> Medical Records - Scanner	0.04950
UR/QA 1 -> ED Coder	0.03544
ED Coder -> UR/QA 1	0.03161
NMH Physician Office - CPOE -> Medical Records - Scanner -> Medical Records - Scanner	0.02888
NMH Physician Office - CPOE -> Medical Records - Scanner -> Medical Records - Scanner -> Medical Records - Scanner	0.02674
UR/QA 1 -> ED Coder -> UR/QA 1	0.02411
UR/QA 1 -> ED Coder -> ED Coder	0.02316
ED Coder -> UR/QA 1 -> ED Coder	0.02296
ED Coder -> ED Coder -> UR/QA 1	0.02291
RX-Pharmacist -> ED Patient Care Staff Nurse	0.02147

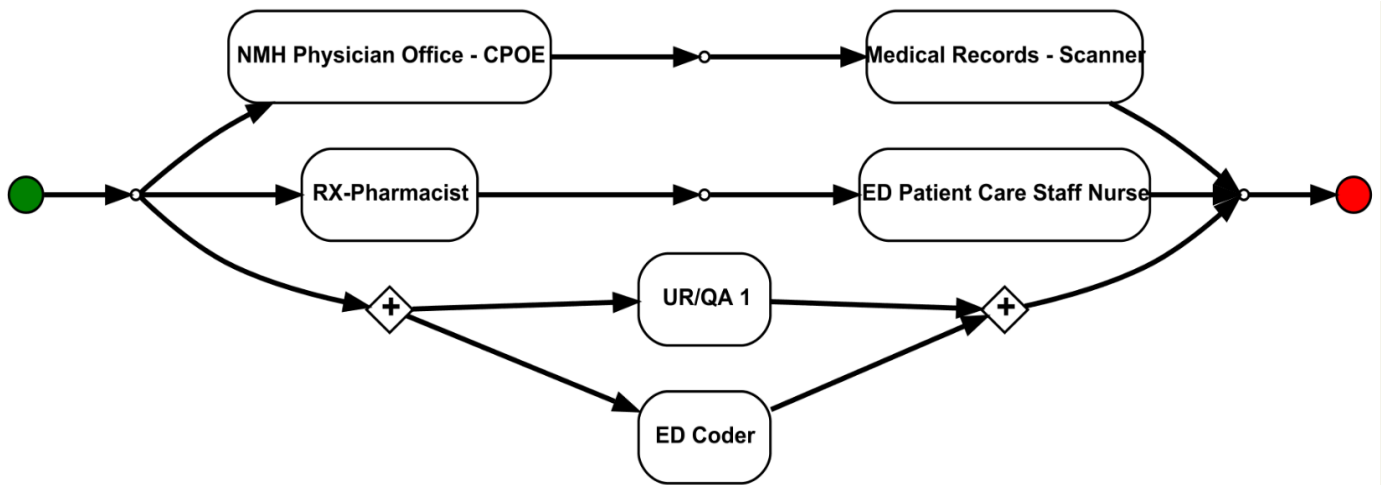


Figure A17 Process graph of workflow w₁₇

Workflow w₁₈

Med Student-CPOE -> SN-OR RN SC	0.02884
SN-OR RN SC -> Med Student-CPOE	0.02869
Advanced Practice Clinician - CPOE -> Medical Records	0.02234
NMH Resident/Fellow-CPOE -> Medical Records - Scanner	0.02112
Medical Records - Scanner -> NMH Resident/Fellow-CPOE	0.02092
SN-OR RN SC -> Med Student-CPOE -> SN-OR RN SC	0.02026
Med Student-CPOE -> SN-OR RN SC -> Med Student-CPOE	0.01985
Medical Records -> Advanced Practice Clinician - CPOE	0.01985
Med Student-CPOE -> Dietary 1	0.01874
Dietary 1 -> Med Student-CPOE	0.01798

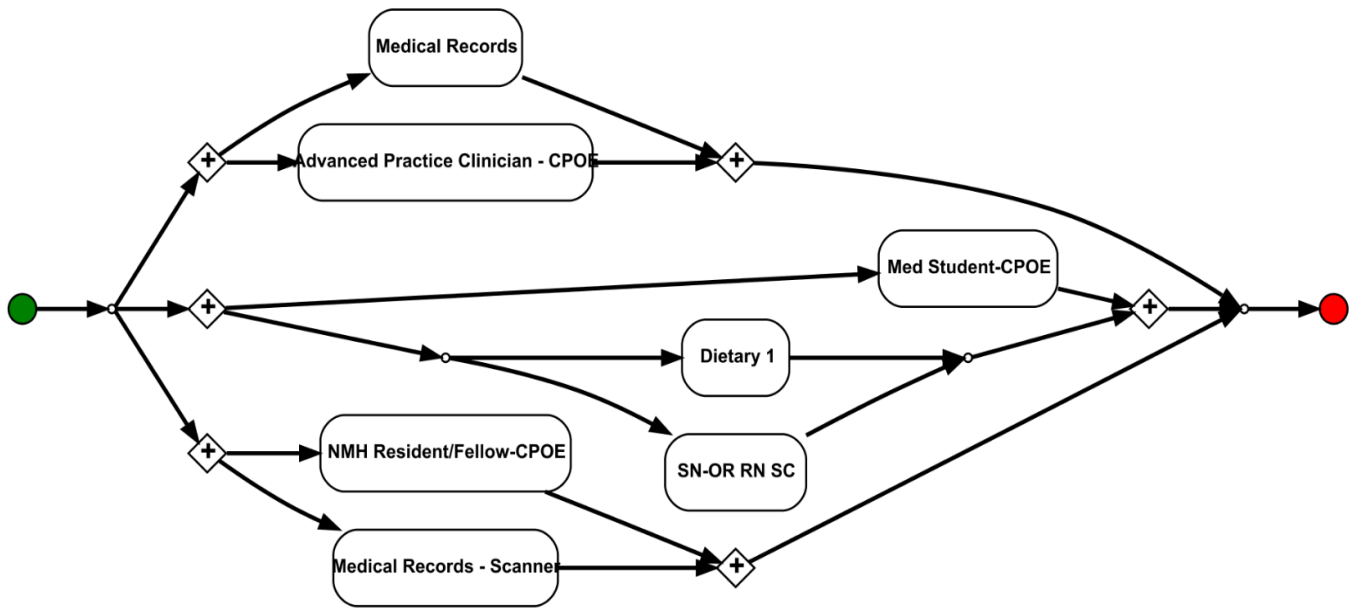


Figure A18 Process graph of workflow w₁₈

Workflow w₁₉

Advanced Practice Clinician - CPOE -> Physician Office	0.01585
Physician Office -> Advanced Practice Clinician - CPOE	0.01518
SN-OR RN SC -> Patient Care Assistive Staff	0.01471
Patient Care Assistive Staff -> SN-OR RN SC	0.01371
Unit Secretary 1 -> Rehab PT	0.01364
Rehab PT -> Unit Secretary 1	0.01331
Respiratory -> SN-RN/Customer Service	0.01237
SN-RN/Customer Service -> NMH Physician Hospitalist-CPOE	0.01150
NMH Physician Hospitalist-CPOE -> SN-RN/Customer Service	0.01124
Physician Office -> Advanced Practice Clinician - CPOE -> Physician Office	0.01087

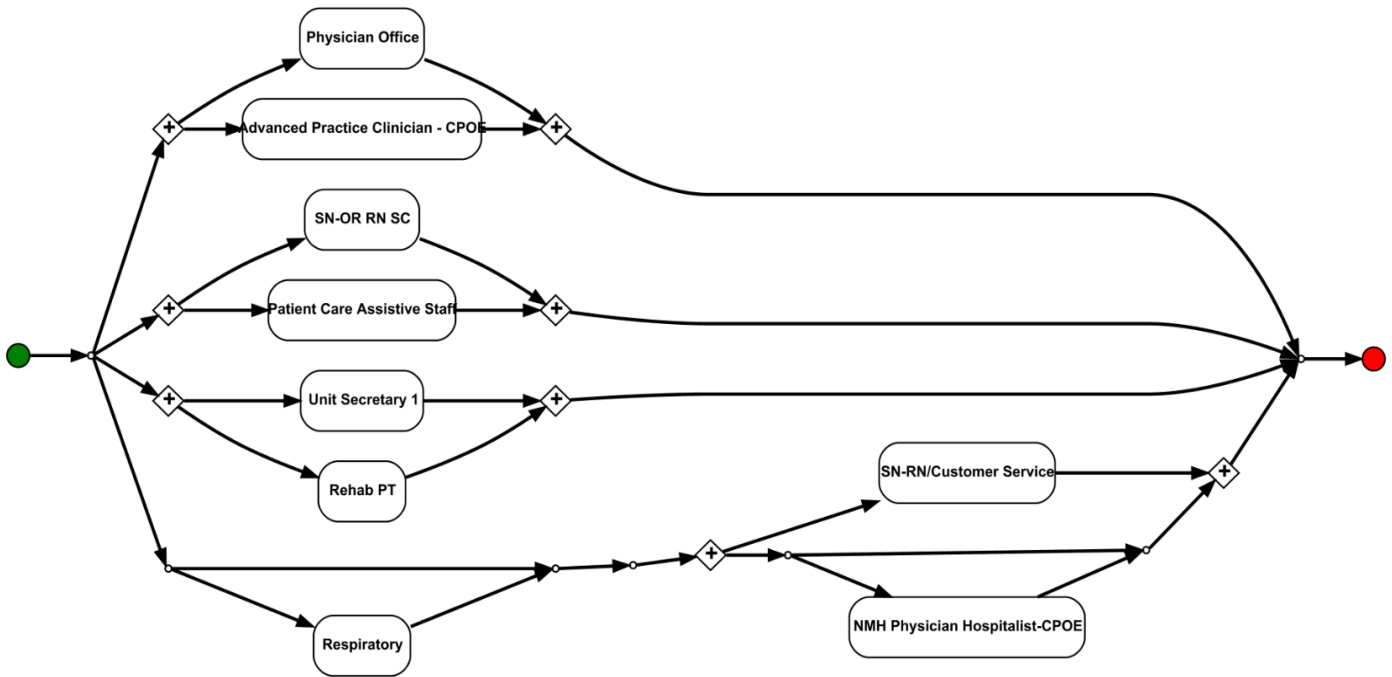


Figure A19 Process graph of workflow w₁₉

Workflow w₂₀

NMH Physician Office - CPOE -> SN-RN/Customer Service	0.04603
SN-RN/Customer Service -> NMH Physician Office - CPOE	0.03152
SN-RN/Customer Service -> NMH Physician Office - CPOE -> SN-RN/Customer Service	0.02764
Unit Secretary 1 -> SN-RN/Customer Service	0.02753
NMH Physician Office - CPOE -> SN-RN/Customer Service -> NMH Physician Office - CPOE	0.02727
NMH Physician Office - CPOE -> SN-RN/Customer Service -> NMH Physician Office - CPOE -> SN-RN/Customer Service	0.02685
SN-RN/Customer Service -> NMH Physician Office - CPOE -> SN-RN/Customer Service -> NMH Physician Office - CPOE	0.02638
NMH Anesthesia-CPOE -> NMH Physician Office - CPOE	0.02559
NMH Physician Office - CPOE -> NMH Anesthesia-CPOE	0.02454
NMH Physician Office - CPOE -> NMH Anesthesia-CPOE -> NMH Physician Office - CPOE	0.01744

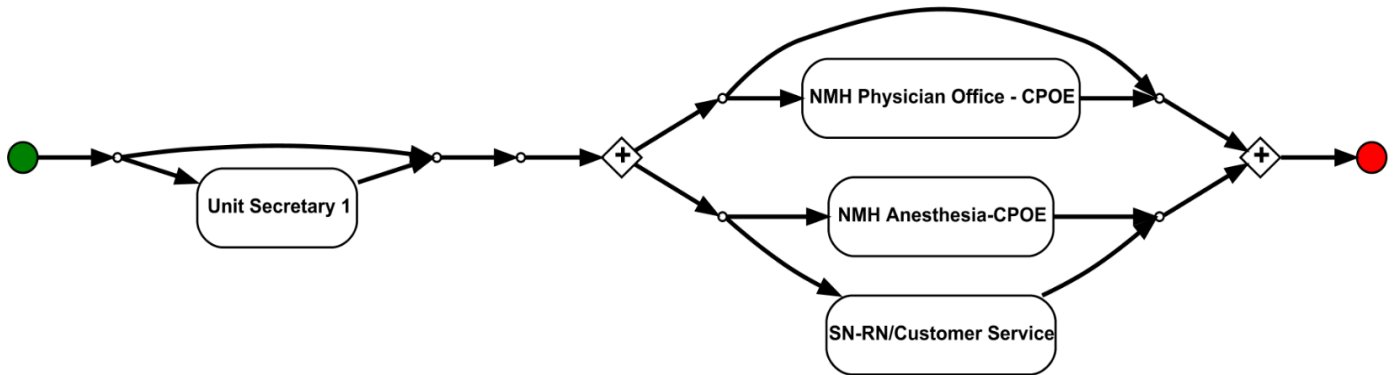


Figure A20 Process graph of workflow w₂₀

Workflow w₂₁

Rehab PT -> Medical Records	0.01790
NMH Physician Hospitalist-CPOE -> Physician Office	0.01708
NMH Physician Hospitalist-CPOE -> Dietary 1	0.01685
Physician Office -> NMH Physician Hospitalist-CPOE	0.01648
Dietary 1 -> NMH Physician Hospitalist-CPOE	0.01648
NMH Physician Hospitalist-CPOE -> Advanced Practice Clinician - CPOE	0.01400
Medical Records -> Rehab PT	0.01336
Patient Care Assistive Staff -> MLPN-Medicating Licensed Practical Nurse	0.01310
RAD - Mgr/RC -> RX-Pharmacist	0.01310
Transfer -> Patient Care Assistive Staff	0.01306

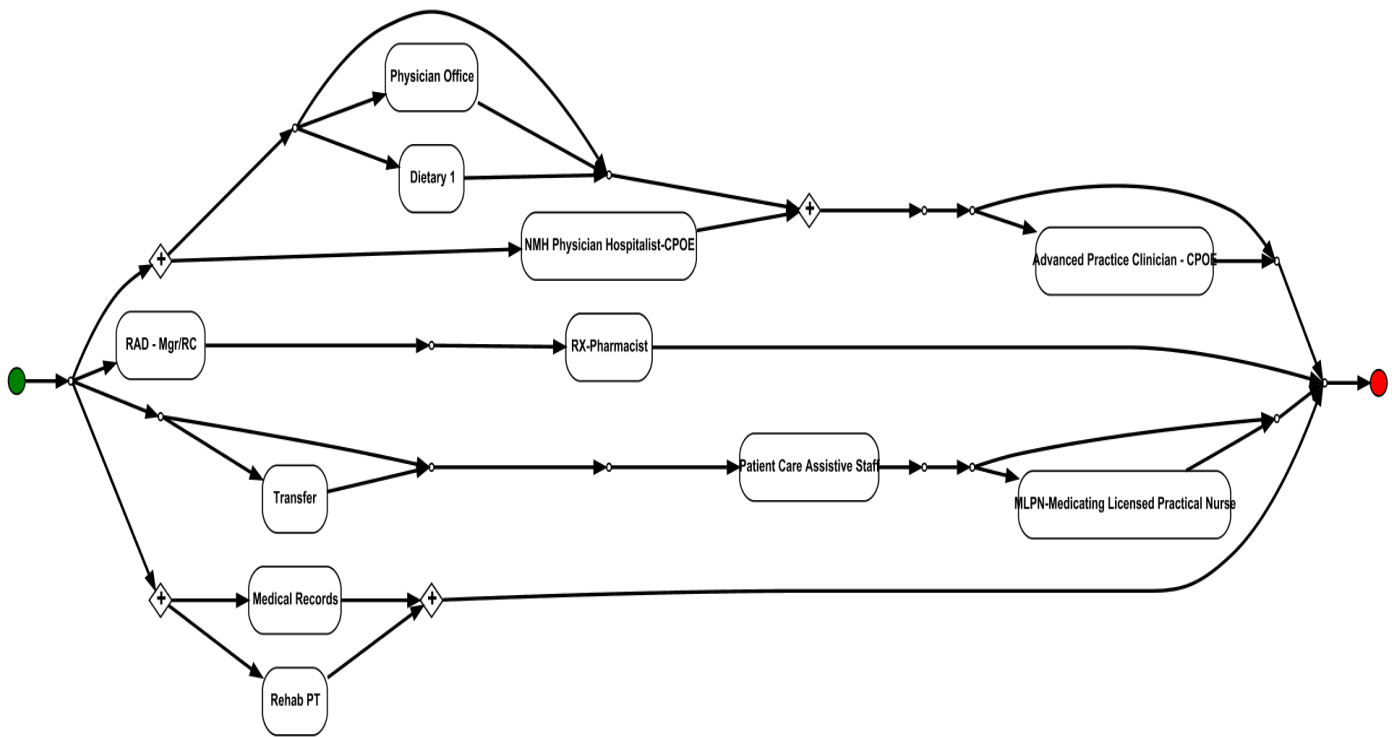


Figure A21 Process graph of workflow w₂₁

Workflow w₂₂

NMH Physician-CPOE -> Medical Records - Scanner	0.03886
Medical Records -> Med Student-CPOE	0.03869
Med Student-CPOE -> Medical Records	0.03750
Medical Records - Scanner -> NMH Physician-CPOE	0.03054
Unit Secretary 2 -> Medical Records	0.02761
NMH Physician-CPOE -> Medical Records - Scanner -> NMH Physician-CPOE	0.02685
Med Student-CPOE -> Medical Records -> Med Student-CPOE	0.02652
Medical Records -> Med Student-CPOE -> Medical Records	0.02647
Unit Secretary 1 -> RAD - Technologist	0.02587
RAD - Technologist -> Unit Secretary 1	0.02576

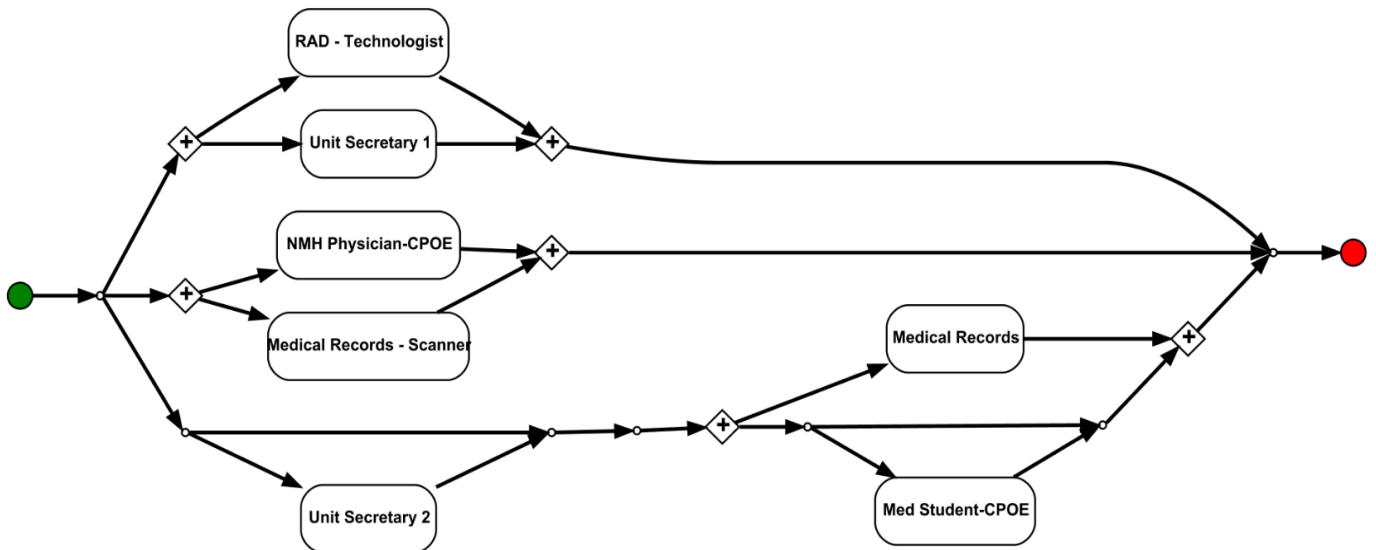


Figure A22 Process graph of workflow w₂₂

Workflow w₂₃

ED Assistant -> ED NMH Physician-CPOE	0.01766
ED NMH Physician-CPOE -> ED Assistant	0.01679
ED NMH Physician-CPOE -> UR/QA 1	0.01586
UR/QA 1 -> ED NMH Physician-CPOE	0.01437
Respiratory -> ED Coder	0.01275
ED Assistant -> ED NMH Physician-CPOE -> ED NMH Physician-CPOE	0.01196
ED NMH Physician-CPOE -> ED Assistant -> ED NMH Physician-CPOE	0.01196
ED Assistant -> Patient Care Staff Nurse	0.01185
ED Assistant -> ED NMH Physician-CPOE -> ED Assistant	0.01185
ED NMH Physician-CPOE -> ED NMH Physician-CPOE -> ED Assistant	0.01185

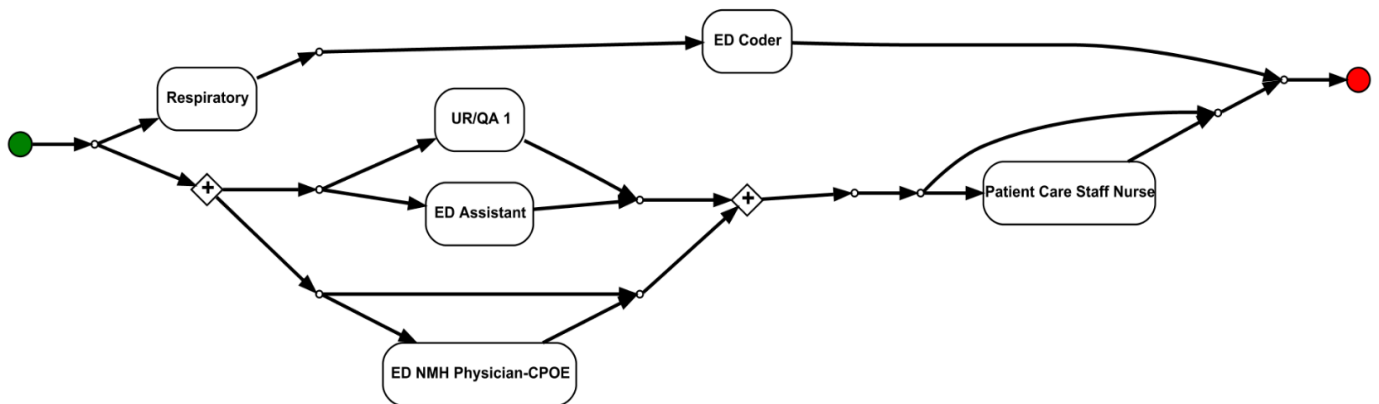


Figure A23 Process graph of workflow w₂₃

Workflow w₂₄

ED Assistant -> ED Unit Secretary	0.01999
NMH Physician-CPOE -> Laboratory 1	0.01614
ED Unit Secretary -> ED Assistant	0.01550
Laboratory 1 -> NMH Physician-CPOE	0.01366
ED Assistant -> ED Unit Secretary -> ED Unit Secretary	0.01246
ED Unit Secretary -> ED Assistant -> ED Assistant	0.01237
ED Assistant -> ED Unit Secretary -> ED Assistant	0.01233
ED Unit Secretary -> ED Assistant -> ED Unit Secretary	0.01229
ED Unit Secretary -> ED Unit Secretary -> ED Assistant	0.01229
ED Unit Secretary -> ED Unit Secretary -> ED Assistant -> ED Unit Secretary	0.01224

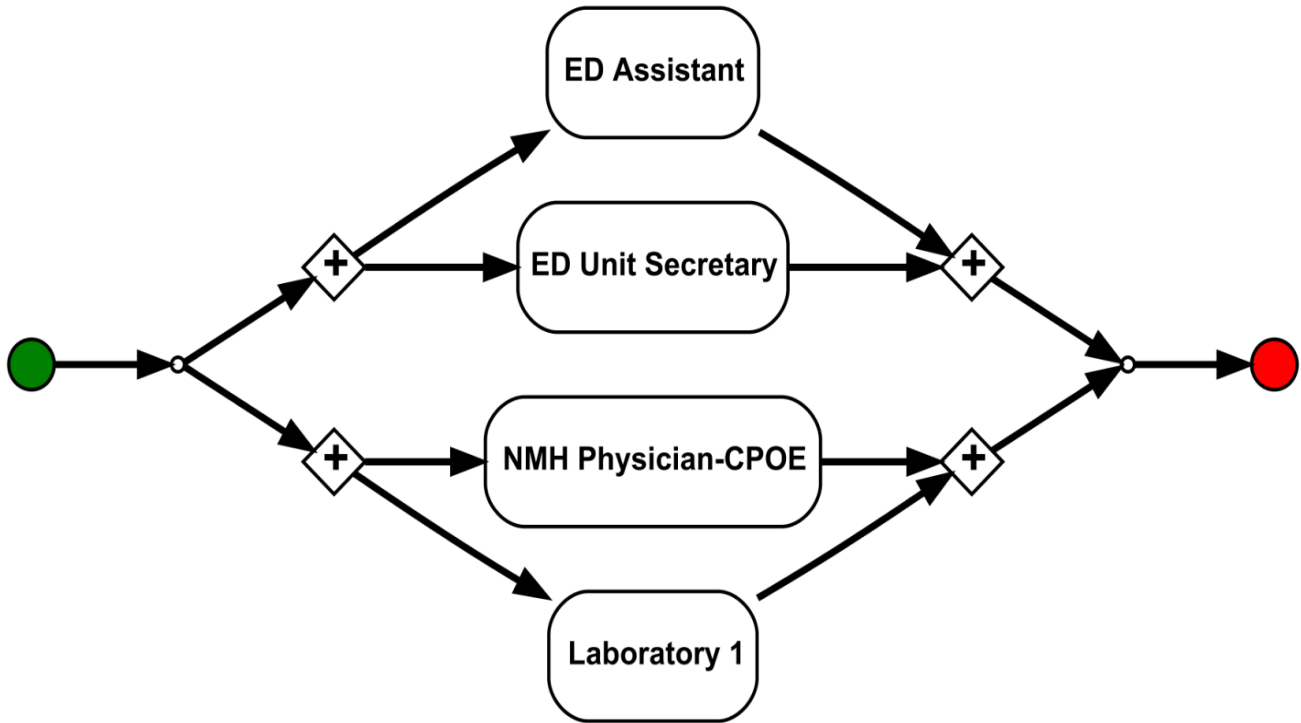


Figure A24 Process graph of workflow w₂₄

Workflow w₂₅

Attending Phys/Prov -> NMH Physician-CPOE	0.09443
Attending Phys/Prov -> NMH Physician Office - CPOE	0.06282
Medical Records -> SN-Management	0.03038
NMH Resident/Fellow-CPOE -> ED Coder	0.02304
Patient Care Staff Nurse - Lactation -> Patient Care Assistive Staff	0.02122
ED Coder -> NMH Resident/Fellow-CPOE	0.02122
Patient Care Assistive Staff -> Patient Care Staff Nurse - Lactation	0.02092
Unit Secretary 2 -> Unit Secretary 2	0.02028
Dietary 1 -> Rehab PT	0.01900
Rehab PT -> Dietary 1	0.01772

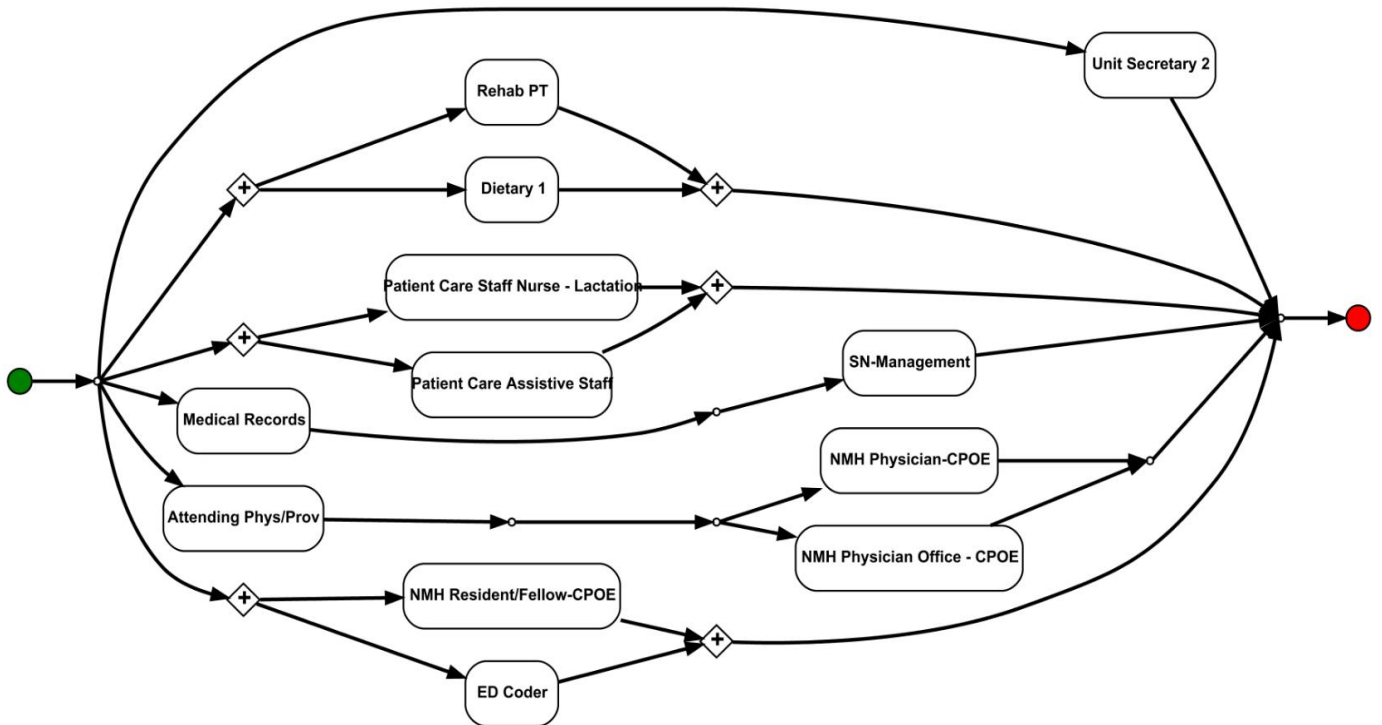


Figure 25 Process graph of workflow w₂₅

Appendix C: 25 Health Condition Collection Topics

As noted in the main manuscript, the framework discovered 25 health condition collection (HCC) topics. Each topic was constrained to consist of the top 10 PheWAS codes with the highest probabilities for that topic. Here we report on each topic, showing its PheWAS codes, the corresponding descriptions, and the probabilities of realizing that code for the topic. Each HCC topic was summarized with a label.

HCC h₁

[Skull associated injury]

1010	Other tests	0.38596
819	Skull fracture and other intracranial injury	0.13715
1008	Internal injury to organs	0.13495
540.11	Acute appendicitis	0.02456
650	Normal delivery	0.02298
805	Fracture of vertebral column without mention of spinal cord injury	0.01889
915	Superficial injury without mention of infection	0.01669
870.3	Other open wound of head and face	0.01574
807	Fracture of ribs	0.01039
562.2	Diverticulitis	0.00976

HCC h₂

[Child birth]

1010	Other tests	0.25000
637	Short gestation; low birth weight; and fetal growth retardation	0.18058
656	Other perinatal conditions	0.16240
656.1	Perinatal jaundice/isoimmunization	0.10374
651	Multiple gestation	0.05558
656.3	Endocrine and metabolic disturbances of fetus and newborn	0.05200
747.11	Cardiac shunt/ heart septal defect	0.02664
656.2	Other respiratory conditions of fetus and newborn	0.02587
647	Infectious & parasitic conditions complicating pregnancy	0.02203
747.13	Congenital anomalies of great vessels	0.01127

HCC h₃

[Hypothyroidism connected]

244	Hypothyroidism	0.26982
285.9	Anemia NOS	0.12089
276.14	Hypopotassemia	0.11665
276.5	Hypovolemia	0.09230
276.12	Hyposmolality and/or hyponatremia	0.05351
275.3	Magnesium metabolism disorder	0.05210
275.51	Hypocalcemia	0.01529
593	Hematuria	0.01076
458.9	Hypotension NOS	0.01048
465	Acute upper respiratory infections	0.00963

HCC h₄

[Oncology]

783	Fever of unknown origin	0.06768
561.1	Diarrhea	0.06376
197	Chemotherapy	0.06141
284.1	Pancytopenia	0.04651
202.2	Non-Hodgkins lymphoma	0.03972
288.11	Neutropenia	0.03815
081	Infection/inflammation of internal prosthetic device, implant or graft	0.03580
204.4	Multiple myeloma	0.03554
962.1	Adverse effects of adrenal cortical steroids	0.03083
287.3	Thrombocytopenia	0.02535

HCC h₅

[Thrombosis]

452	Venous embolism & thrombosis	0.19148
286.5	Hemorrhagic disorder due to intrinsic circulating anticoagulants	0.09945
452.2	Deep vein thrombosis	0.09478
415.1	Pulmonary embolism and infarction	0.04698
286.9	Abnormal coagulation profile	0.03846
276.5	Hypovolemia	0.03819
282.5	Sickle cell anemia	0.03407
695.42	Systemic lupus erythematosus	0.03022
415	pulmonary heart disease	0.02857
288.2	Elevated white blood cell count	0.02802

HCC h₆

[Diabetes]

250.2	Type 2 diabetes	0.15440
272.1	Hyperlipidemia	0.13317
401.1	Essential hypertension	0.11056
250.3	Insulin pump user	0.07031
707.2	Chronic ulcer of leg or foot	0.05018
681.5	Cellulitis and abscess of leg	0.04577
250.24	Type 2 diabetic neuropathy	0.04136
250.6	Polyneuropathy in diabetes	0.04053
443.9	Peripheral arterial disease	0.02123
536.3	Gastroparesis	0.01902

HCC h₇

[Osteoarthritis]

401.1	Essential hypertension	0.15078
530.11	GERD	0.10161
740.1	Osteoarthritis; localized	0.10134
272.11	Hypercholesterolemia	0.06993
743.11	Osteoporosis	0.05381
740.9	Osteoarthritis NOS	0.03851
296.2	Depression	0.03633
714.1	Rheumatoid arthritis	0.03278
720.1	Spinal stenosis of lumbar region	0.02513
1015	Effects of other external causes	0.02404

HCC h₈

[Urinary infection]

591	Urinary tract infection	0.22461
707.1	Decubitus ulcer	0.16335
344	Other paralytic syndromes	0.04819
595	Hydronephrosis	0.02804
411.8	Chronic ischemic heart disease	0.02695
590	Infections of kidney	0.02668
596.5	Functional disorders of bladder	0.02614
335	Multiple sclerosis	0.02586
411.3	Angina pectoris	0.02233
285.2	Anemia of chronic disease	0.02151

HCC h₉

[Late pregnancy]

1010	Other tests	0.32474
665	Obstetrical/birth trauma	0.14830
645	Late pregnancy and failed induction	0.12573
649	Other conditions of the mother complicating pregnancy	0.11489
658	Problems associated with amniotic cavity and membranes	0.09320
661	Fetal distress and abnormal forces of labor	0.07093
402	Elevated blood pressure reading	0.00938
261.2	Vitamin B-complex deficiencies	0.00352
351	Other peripheral nerve disorders	0.00352
597.1	Urethral stricture (not specified as infectious)	0.00293

HCC h₁₀

[Sepsis]

585.1	Acute renal failure	0.10666
480	Pneumonia	0.07747
994.2	Sepsis	0.07299
509.1	Respiratory failure	0.06875
276.41	Acidosis	0.06593
389	Hearing loss	0.05628
276.12	Hyposmolality and/or hyponatremia	0.04639
797	Shock	0.04497
260	Protein-calorie malnutrition	0.03956
507	Pleurisy; pleural effusion	0.03508

HCC h₁₁

[Prostate]

272.1	Hyperlipidemia	0.15198
401.1	Essential hypertension	0.15061
600	Hyperplasia of prostate	0.10215
496	Chronic airway obstruction	0.08921
185	Prostate cancer	0.08260
599.2	Retention of urine	0.04598
250.2	Type 2 diabetes	0.03662
189.21	Bladder cancer	0.02285
496.1	Emphysema	0.02065
290.1	Dementias	0.01432

HCC h₁₂

[Birth trauma]

665	Obstetrical/birth trauma	0.43332
663	Umbilical cord complications during labor and delivery	0.21789
649	Other conditions of the mother complicating pregnancy	0.11699
659	Indications for care or intervention related to labor and delivery NEC	0.09381
655.1	Abnormality in fetal heart rate or rhythm	0.06054
658	Problems associated with amniotic cavity and membranes	0.00273
642.1	Preeclampsia and eclampsia	0.00245
010	Tuberculosis	0.00218
655	Known or suspected fetal abnormality	0.00191
669	Complications of labor and delivery NEC	0.00191

HCC h₁₃

[Cancer]

198.4	Secondary malignant neoplasm of liver	0.15577
198.6	Secondary malignancy of bone	0.11517
165.1	Lung cancer	0.104845
198	Secondary malignant neoplasm	0.04668
198.2	Secondary malignancy of lung	0.04643
198.1	Secondary malignancy of lymph nodes	0.04592
153.2	Colon cancer	0.03608
198.3	Secondary malignant neoplasm of digestive systems	0.03381
563	Constipation	0.06485
174.11	Breast cancer	0.10295

HCC h₁₄

[Cerebrovascular disease]

401.1	Essential hypertension	0.16744
433.31	Transient cerebral ischemia	0.07977
433.8	Late effects of cerebrovascular disease	0.07324
345	Epilepsy, recurrent seizures, convulsions	0.04846
290.3	Persistent mental disorders due to other conditions	0.03730
345.3	Convulsions	0.03539
788	Syncope and collapse	0.03267
433.21	Ischemic stroke	0.02995
272.1	Hyperlipidemia	0.02777
798	Malaise and fatigue	0.02532

HCC h₁₅

[Depression]

296.2	Depression	0.08719
300.1	Anxiety disorder	0.08134
789	Nausea and vomiting	0.07270
785	Abdominal pain	0.05794
338	Pain NEC	0.05265
760	Back pain	0.05153
300.4	Dysthymic disorder	0.04819
340	Migraine	0.04262
563	Constipation	0.03788
280.1	Iron deficiency anemias	0.03705

HCC h₁₆

[Heart failure]

427.21	Atrial fibrillation	0.20371
428.1	Systolic/diastolic heart failure	0.18946
428	Heart failure	0.10423
425.1	Primary/intrinsic cardiomyopathies	0.05539
415	pulmonary heart disease	0.04454
427.12	Paroxysmal ventricular tachycardia	0.03730
395.1	Nonthematic mitral valve disorders	0.03617
427.22	Atrial flutter	0.03595
426.92	Cardiac defibrillator in situ	0.03414
411.8	Chronic ischemic heart disease	0.02962

HCC h₁₇

[Fetal abnormality]

652	Malposition and malpresentation of fetus or obstruction	0.16853
658	Problems associated with amniotic cavity and membranes	0.11036
655	Known or suspected fetal abnormality	0.06310
669	Complications of labor and delivery NEC	0.06076
635.3	Placenta previa and abruption placenta	0.05895
636.2	Early onset of delivery	0.05765
659	Indications for care or intervention related to labor and delivery NEC	0.05323
661	Fetal distress and abnormal forces of labor	0.05012
651	Multiple gestation	0.04856
655.1	Abnormality in fetal heart rate or rhythm	0.04804

HCC h₁₈

[Essential hypertension and hyperlipidemia]

401.1	Essential hypertension	0.20079
250.2	Type 2 diabetes	0.16901
327.32	Obstructive sleep apnea	0.14411
272.1	Hyperlipidemia	0.09881
278.11	Morbid obesity	0.09828
278.1	Obesity	0.07815
274.1	Gout	0.02172
465	Acute upper respiratory infections	0.00980
450	Noninfectious disorders of lymphatic channels	0.00848
550.2	Diaphragmatic hernia	0.00450

HCC h₁₉

[Tobacco and alcohol]

316	Substance addiction and disorders	0.12156
318	Tobacco use disorder	0.12129
317.1	Alcoholism	0.07686
296.1	Bipolar	0.05914
317	Alcohol-related disorders	0.04443
418	Nonspecific chest pain	0.04061
280.1	Iron deficiency anemias	0.02944
296.2	Depression	0.02644
495.2	Asthma with exacerbation	0.02317
401.1	Essential hypertension	0.02017

HCC h₂₀

[Anemia connected]

285.9	Anemia NOS	0.19954
427.3	Other specified cardiac dysrhythmias	0.08314
250.42	Other abnormal glucose	0.07110
1013	Asphyxia and hypoxemia	0.04472
508	Pulmonary collapse; interstitial/compensatory emphysema	0.04472
458.9	Hypotension NOS	0.04444
276.6	Fluid overload	0.03784
287.3	Thrombocytopenia	0.03354
850	Hemorrhage or hematoma complicating a procedure	0.02982
080	Postoperative infection	0.02896

HCC h₂₁

[Gastroesophageal reflux disease]

530.11	GERD	0.22110
401.1	Essential hypertension	0.18709
495	Asthma	0.17498
272.1	Hyperlipidemia	0.05881
550.2	Diaphragmatic hernia	0.02364
427.7	Tachycardia NOS	0.02220
532	Dysphagia	0.01268
568.1	Peritoneal adhesions (postoperative) (post infection)	0.01182
562.2	Diverticulitis	0.01009
193	Thyroid cancer	0.00922

HCC h₂₂

[Liver disease]

585.1	Acute renal failure	0.06854
572	Ascites (nonmalignant)	0.05804
571.51	Cirrhosis of liver without mention of alcohol	0.04307
571.8	Liver abscess and sequelae of chronic liver disease	0.03388
276.12	Hyposmolality and/or hyponatremia	0.03256
317.11	Alcoholic liver damage	0.02967
569.2	Gastrointestinal complications	0.02889
560.1	Paralytic ileus	0.02784
573.2	Liver replaced by transplant	0.02600
562.1	Diverticulosis	0.02468

HCC h₂₃

[Coronary atherosclerosis]

411.4	Coronary atherosclerosis	0.52697
411.2	Myocardial infarction	0.16604
272.1	Hyperlipidemia	0.07974
411.8	Chronic ischemic heart disease	0.03705
443.9	Peripheral arterial disease	0.02697
854	Mechanical complications of cardiac/vascular device, implant, and graft	0.01595
442.11	Abdominal aortic aneurysm	0.01454
411.1	Unstable angina (intermediate coronary syndrome)	0.00962
285.1	Acute post hemorrhagic anemia	0.00586
585.3	Chronic renal failure	0.00563

HCC h₂₄

[Mother complicating pregnancy]

649	Other conditions of the mother complicating pregnancy	0.16643
654	Abnormality pelvic soft tissues & organs complicating pregnancy	0.16155
659	Indications for care or intervention related to labor and delivery NEC	0.12396
218.1	Uterine leiomyoma	0.07633
665	Obstetrical/birth trauma	0.06284
642	Hypertension complicating pregnancy	0.03558
649.1	Gestational diabetes	0.03300
626.12	Excessive or frequent menstruation	0.02095
647	Infectious & parasitic conditions complicating pregnancy	0.01865
615	Endometriosis	0.01808

HCC h₂₅

[Kidney disease]

401.22	Hypertensive chronic kidney disease	0.21740
585.3	Chronic renal failure	0.14946
585.32	End stage renal disease	0.09533
585.31	Renal dialysis	0.05808
587	Kidney replaced by transplant	0.05654
276.13	Hyperpotassemia	0.05282
585.1	Acute renal failure	0.04624
285.21	Anemia in chronic kidney disease	0.04208
250.22	Type 2 diabetic nephropathy	0.02279
250.7	Diabetic retinopathy	0.02060