A standardized framework for risk-based assessment of treatment effect heterogeneity in observational healthcare databases

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Abstract

One of the aims of the Observational Health Data Sciences and Informatics (OHDSI) initiative is population-level treatment effect estimation in large observational databases. Since treatment effects are well-known to vary across groups of patients with different baseline risk, we aimed to extend the OHDSI methods library with a framework for risk-based assessment of treatment effect heterogeneity. The proposed framework consists of five steps: 1) definition of the problem, i.e. the population, the treatment, the comparator and the outcome(s) of interest; 2) identification of relevant databases; 3) development of a prediction model for the outcome(s) of interest; 4) estimation of propensity scores within strata of predicted risk and estimation of relative and absolute treatment effect within strata of predicted risk; 5) evaluation and presentation of results. We demonstrate our framework by evaluating heterogeneity of the effect of angiotensin-converting enzyme (ACE) inhibitors versus beta blockers on a set of 9 outcomes of interest across three observational databases. With increasing risk of acute myocardial infarction we observed increasing absolute benefits, i.e. from -0.03% to 0.54% in the lowest to highest risk groups. Cough-related absolute harms decreased from 4.1% to 2.6%. The proposed framework may be useful for the evaluation of heterogeneity of treatment effect on observational data that are mapped to the OMOP Common Data Model. The proof of concept study demonstrates its feasibility in large observational data. Further insights may arise by application to safety and effectiveness questions across the global data network.

Keywords: observational data, heterogeneity of treatment effect, risk stratification, subgroup analysis

1 Introduction

Understanding how a treatment's effect varies across patients—a concept described as heterogeneity of treatment effects (HTE)—has been central to the agenda for both personalized (or precision) medicine and comparative effectiveness research. More formally, HTE has been defined as the non-random variability in the direction or magnitude of a treatment effect, in which the effect is measured using clinical outcomes [1]. Usually, analyses focus on the relative scale, where treatment effects are assessed one at a time in patient subgroups defined from single covariates, an approach that suffers from low power and multiplicity issues [2,3]. However, even with well-established constant relative effects, treatment benefit (or harm) may vary substantially on the absolute scale.

More recently, "predictive" HTE analyses have been described as approaches that provide predictions of potential outcomes in a particular patient with one intervention versus an alternative, taking into account multiple relevant patient characteristics [4]. We focus on "risk modeling" approaches where patients are divided into risk strata using either an existing or an internally developed risk prediction model. Risk-stratum-specific estimates provide an overview of the evolution of treatment effects with increasing risk both on the relative and the absolute scale. Recently, systematic guidance on the application of such methods has been developed [5,6].

While these approaches were developed for application in randomized controlled trials (RCTs), observational databases are also an appealing substrate. Observational healthcare databases, such as administrative claims and electronic health records, are already highly available for the analysis of pharmacoepidemiologic research questions [7,8]. They are also often larger than many typical trials, providing excellent power for HTE analysis, including heterogeneous populations. However, unlike RCTs, treatment effects are subject to confounding while the unique structure of different databases calls for database-specific analysis plans that are often not easily transportable.

The Observational Health Data Sciences and Informatics (OHDSI) collaborative has established an international network of data partners and researchers that aim to bring out the value of health data through large-scale analytics by mapping all available databases to the Observational Medical Outcomes Partnership (OMOP) Common Data Model (CDM) [9,10]. The common data structure enables analyses at a very large scale. For example, in a recent study, a large set of first-line treatments for hypertension was compared with respect to 55 outcomes in a network of databases, including 4.9 million patients from around the world [11].

We aimed to develop a framework for risk-based assessment of treatment effect heterogeneity in high-dimensional observational data, which extends the existing guidelines of the RCT setting. We implemented the framework using existing OHDSI methods for use in the OMOP-CDM, including the patient-level prediction framework and the population-level effect estimation framework based on new-user cohort design [12,13]. As a proof-of-concept we analyzed heterogeneity of the effects of first-line hypertension treatment: we compared the effect of angiotensin

converting enzyme (ACE) inhibitors to beta blockers on 9 outcomes across three different US claims databases.

2 Materials and Methods

The proposed framework defines 5 distinct steps that enable a standardized approach for risk-based assessment of treatment effect heterogeneity for databases mapped to the OMOP-CDM. These are: 1) general definition of the research aim; 2) identification of the database within which the analyses will be performed; 3) a prediction step where internal or external prediction models are used to assign patient-level risk predictions; 4) an estimation step where absolute and relative treatment effects are estimated within risk strata; 5) presentation and evaluation of the results. A overview of the procedure can be seen in Figure 1.

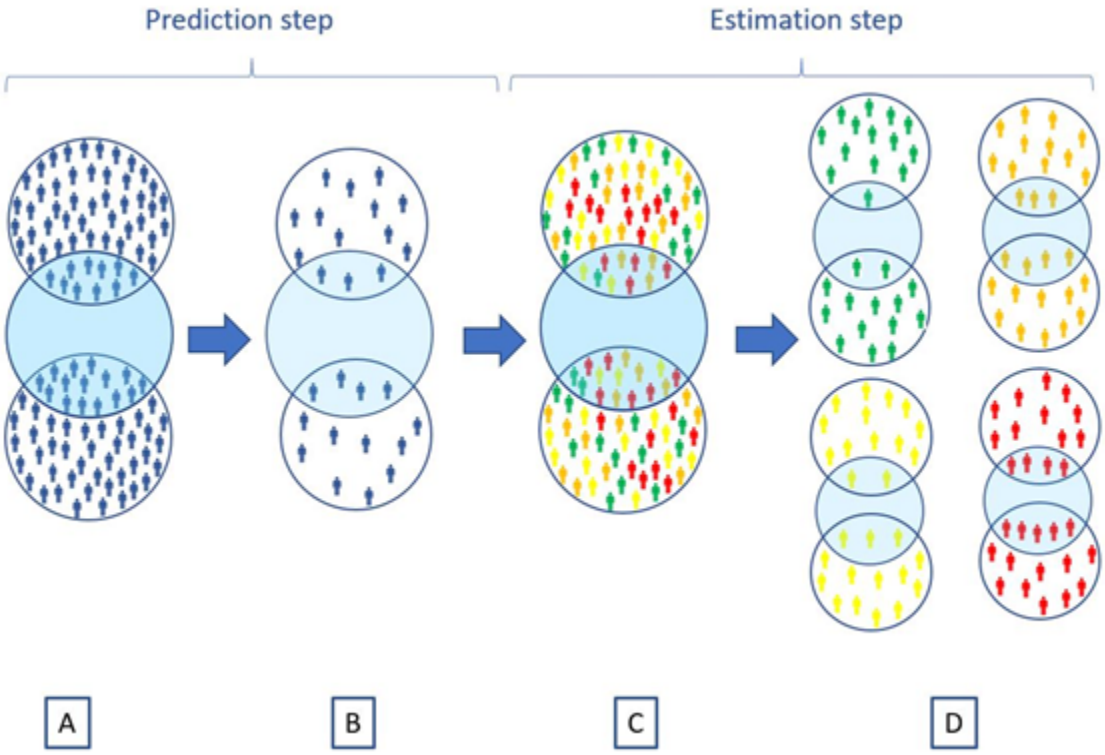

Figure 1: (A) Starting from a treatment (top), a comparator (bottom) and an outcome (middle) cohort we estimate the propensity scores on the entire target population. (B) We match patients on the propensity scores and estimate the prediction model. Since we match patients we develop the prediction model on smaller subset of the initial population and, therefore, the number of patients is smaller in B compared to A. (C) We apply the prediction model on the entire population (green: lower 25% of the risk distribution; yellow: patients with risk between 25% and 50% of the risk distribution; orange: patients with risk between 50% and 75% of the risk distribution; red: patients at risk higher than 75% of the risk distribution). (D) We separate in risk subgroups, here quarters. Within risk quarters propensity scores are estimated again and relative and absolute treatment effects are estimated.

2.1 Step 1: General definition of the problem

The typical research aim is: "to compare the effect of treatment T to a comparator treatment C in patients with disease D with respect to outcomes $O_1, \ldots, O_n$". At least three cohorts are defined:

- A single treatment cohort (T) which includes patients with disease D receiving the target treatment of interest. For example, a set of hypertension patients within a database that receive angiotensin-converting enzyme inhibitors, followed from the time of initiation until the time of censoring.
- A single comparator cohort (C) which includes patients with disease D receiving the comparator (control) treatment. For example, a set of patients in a database that receive beta blockers, followed from the time of initiation until the time of censoring.
- One or more outcome cohorts ($O_1, \ldots, O_n$) that contain patients developing the outcomes of interest. For example, the set of patients in a database that have at least one occurrence of acute myocardial infarction in their record.

Note "cohort" refers to a set of persons who satisfy one or more criteria for a duration of time. The term can be used interchangeably with the term phenotype.

2.2 Step 2: Identification of the database

The aim of this step is the inclusion of databases that represent the patient population of interest. The inclusion of multiple databases potentially increases the generalizability of results. Furthermore, the cohorts should preferably have adequate sample size to ensure precise effect estimation, even within smaller risk strata.

2.3 Step 3: Prediction

We adopt the standardized framework for the generation of patient-level prediction models using observational data that ensures adherence to existing guidelines [14,15]. This prediction framework requires the definition of two essential cohorts: a target cohort and an outcome cohort.

To generate the target cohort we pool the already defined treatment cohort and comparator cohort. To avoid deferentially fitting the prediction model to patients across treatment arms, thus introducing spurious interactions with treatment [16,17], we develop the patient-level prediction model in the propensity score-matched (1:1) subset of the population. Finally, we need to define the time horizon within which we aim to make predictions and we also need to select the machine-learning algorithm we want to use to generate patient-level predictions. Currently, the available options are regularized logistic regression, random forest, gradient boosting machines, decision tree, naive Bayes, K-nearest neighbors, neural network and deep learning (convolutional neural networks, recurrent neural

network and deep nets).

2.4 Step 4: Estimation

The aim of this step is the estimation of treatment effects (both on the relative and the absolute scale) within risk strata—typically 4 risk quarters—defined using the prediction model of step 3. Any appropriate method for the evaluation of relative and absolute treatment effects can be considered, as long as the this is done consistently in all risk strata. Common approaches are odds ratios or hazard ratios for the relative scale and differences in proportions or differences in Kaplan-Meier estimates on the absolute scale, depending on the problem at hand. We estimate propensity scores within risk strata which we then use to match patients from different treatment cohorts or stratify them into groups with similar propensity scores or to weigh each patient's contribution to the estimation process [18].

2.5 Step 5: Result presentation and evaluation

In the presence of a positive treatment effect and a well-discriminating prediction model we expect an increasing pattern of the differences in the absolute scale, even if the relative effects remain constant on the relative scale across risk strata. Results should be presented side-by-side on a forest-plot-like format, so that the evolution of treatment effects across risk strata is visible both on the relative and the absolute scale.

A performance overview of the derived prediction models, including discrimination and calibration both in the propensity score matched subset, the entire population and separately for treated and comparator patients should also be reported. This is quite relevant as the performance of the prediction models is directly related to our ability to single out patient subgroups where treatment may be highly beneficial or unsafe. Kent et al [19] demonstrated that the event rate and the discriminative ability of the prediction model can predict very well the distribution of predicted risk. Lower event rate and higher c-statistic (given good calibration) result in high risk heterogeneity, thus making estimated average treatment effects uninformative. In this case, risk stratified analysis of HTE can be more effective in singling out patient subgroups that stand to benefit (or be harmed) most by treatment in question.

In each risk stratum we need to evaluate if adequate covariate balance was achieved accounting for measured confounding. If that is not the case, interpretation of the results may be problematic. Common approaches include evaluation of the overlap of propensity score distributions and calculation of standardized covariate differences before and after propensity score adjustment.

3 Results

As a proof of concept, we focus on the comparison of angiotensin converting enzyme (ACE) inhibitors to beta blockers. ACE inhibitors are among the most common treatment classes for hypertension, with well-established effectiveness. Beta blockers, even though initially widely used for the treatment of hypertension, more recent trials and meta-analyses have cast doubt on their relative effectiveness [20]. As a result, newer US guidelines do not consider them for initial treatment for hypertension while in the EU guidelines combination with other antihypertensive treatments is recommended [21,22]. However, another meta-analysis suggested that the efficacy profile of beta blockers is similar to other major treatment classes in younger hypertensive patients and, thus, countries like Canada still include them as a first-line treatment candidate [23,24].

3.1 Step 1: General definition of the problem

We consider the following research aim: "compare the effect of ACE-inhibitors (T) to the effect of beta blockers (C) in patients with established hypertension (D) with respect to 9 outcomes ($O_1, \ldots, O_9$)". The cohorts are:

- Treatment cohort: Patients receiving any drug within the ACE-inhibitor class with at least one year of follow-up before treatment initiation and a recorded hypertension diagnosis within that year.
- Comparator cohort: Patients receiving any drug within the beta blocker class with at least one year of follow-up before treatment initiation and a recorded hypertension diagnosis within that year.
- Outcome cohorts: We consider 3 main and 6 safety outcome cohorts. These are patients in the database with a diagnosis of: acute myocardial infarction (MI); hospitalization with heart failure; ischemic or hemorrhagic stroke (efficacy outcomes); hypokalemia; hyperkalemia; hypotension; angioedema; cough; abnormal weight gain (safety outcomes).

All cohort definitions can be found in the supplementary material.

3.2 Step 2: Identification of the databases

We used the following databases:

- IBM MarketScan Medicare Supplemental Beneficiaries (MDCR): Represents health services of retirees (aged 65 or older) in the United States with primary or Medicare supplemental coverage through privately insured fee-for-service, point-of-service or capitated health plans. These data include adjudicated health insurance claims (e.g. inpatient, outpatient and outpatient pharmacy). Additionally, it captures laboratory tests for a subset of the covered lives.
- IBM MarketScan Medicaid (MDCD): Adjudicated US health insurance claims for Medicaid enrollees from

multiple states. It includes hospital discharge diagnoses, outpatient diagnoses and procedures and outpatient pharmacy claims as well as ethnicity and Medicare eligibility.

- IBM MarketScan Commercial Claims and Encounters (CCAE): Data from individuals enrolled in US employer-sponsored insurance health plans. The data includes adjudicated health insurance claims (e.g. inpatient, outpatient, and outpatient pharmacy) as well as enrollment data from large employers and health plans who provide private healthcare coverage to employees, their spouses and dependents. Additionally, it captures laboratory tests for a subset of the covered lives.

3.3 Step 3: Prediction

We developed separate prediction models for all efficacy outcomes (acute MI, hospitalization with heart failure and hemorrhagic or ischemic stroke) in each database. More specifically, we first estimated propensity scores using LASSO logistic regression and a large set of baseline covariates including demographics, drug exposures, diagnoses, measurements and medical devices. The prediction models were estimated on the propensity score matched (1:1) subset of the population, using caliper of 0.2 and after excluding patients having the outcomes any time prior to treatment initiation. We chose a time horizon of 2 years after inclusion into the target cohort. For this demonstration, we developed the prediction models using LASSO logistic regression with 3-fold cross validation for hyper-parameter selection. We chose a time horizon of 2 years after inclusion into the target cohort. For this demonstration, we developed the prediction models using LASSO logistic regression with 3-fold cross validation for hyper-parameter selection.

3.4 Step 4: Estimation

We used patient-level predictions to stratify the patient population into 4 risk quarters. Within risk strata, relative effects were estimated using Cox regression and absolute effects were estimated from the Kaplan-Meier estimate differences at 2 years after treatment initiation. To adjust for observed confounding within risk strata, we estimated propensity scores using the same approach as in the development of prediction models. We used the estimated propensity scores to stratify patients into 5 strata, within each risk quarter.

3.5 Step 5: Result presentation and evaluation

We present the results of the analysis in the CCAE database with stratification based on risk predictions of acute MI. Results of analyses in the other databases and with other risk stratifications are included in the supplementary material.

For each outcome and in each risk stratum there were adequate numbers of patients (Table 1). The discriminative

ability of the prediction models was moderate in the matched development subset (c-index 0.76 for acute MI ; 0.79 for hospitalization with heart failure; 0.74 for stroke;), in the general population (c-index 0.74 for acute MI; 0.77 for hospitalization with heart failure; 0.73 for stroke), in the treatment cohort (c-index for acute MI it was 0.71, for hospitalization with heart failure was 0.76 and for stroke it was 0.72) and in the comparator cohort (c-index for acute MI it was 0.79 for hospitalization with heart failure was 0.79 and for stroke it was 0.75).

Table 1: Number of patients, person years and events within quarters of predicted risk for hospitalization with heart failure for the 3 main outcomes of the study (acute myocardial infarction, hospitalization with heart failure and ischemic or hemorrhagic stroke).

		ACE inhibitors			Beta blockers		
Outcome	Risk quarter	Persons	Person years	Events	Persons	Person years	Events
Acute myocardial infarction	1	161,099	276,171	203	133,977	220,633	135
	2	204,882	372,197	534	90,193	169,231	321
	3	214,413	393,583	117	80,662	150,035	535
	4	204,167	351,727	2,095	90,908	154,419	1,520
Heart failure (hosp)	1	146,259	249,809	228	126,387	206,706	378
	2	188,006	341,014	457	84,280	158,425	340
	3	218,052	399,394	826	83,421	155,222	570
	4	230,226	400,330	2,012	98,380	169,139	1,773
Stroke (ischemic or hemorrhagic)	1	146,069	294,484	299	126,264	206,453	320
	2	187,524	340,234	554	84,000	157,913	351
	3	217,070	397,830	947	83,038	154,587	521
	4	226,128	393,861	1,718	97,628	167,810	1,077

Relative treatment effects of ACE-inhibitors vs beta blockers increased in favor of ACE-inhibitors (hazard ratios decreased) with increasing acute MI risk, resulting in more pronounced absolute risk differences (ARD) with increasing acute MI risk (Figure 2).

In general, with increasing acute MI risk we observed an increasing pattern in terms of absolute benefit for the main outcomes, while the absolute harms did not increase for the safety outcomes. More specifically, patients in the low risk quarter did not receive absolute benefit (-0.03%) while absolute risk was 0.54% lower (95% confidence interval 0.36%—0.71%) for patients in the highest risk quarter. In contrast, the absolute and relative effects of

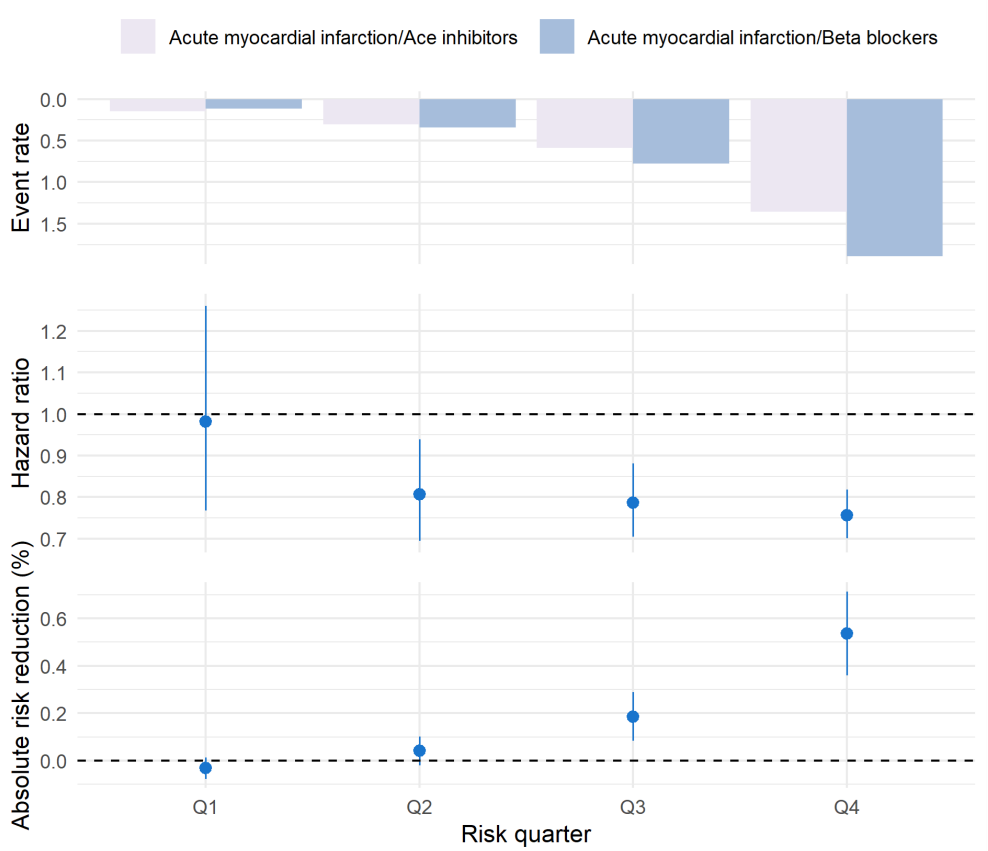

Figure 2: Overview of heterogeneity of ACE-inhibitors treatment within strata of predicted risk of acute MI. The top panel contains the observed acute rates of ACE-inhibitors and beta blockers within each quarter of predicted acute MI risk. These are derived using the KaplanMeier estimates at 730 days after inclusion. The middle panel, contains the hazard ratios of comparing ACE-inhibitors to beta blockers with regard to acute MI. These are estimated using Cox proportional hazards regression within quarters of predicted acute MI risk. The bottom panel contains absolute risk reduction for ACE-inhibitors compared to beta blockers. These are derived as the difference in Kaplan-Meier estimates at 730 after inclusion. Hazard ratios in the middle panel show a decreasing trend with increasing acute MI risk. Given the rather good discrimination of the prediction model (AUC=0.74), this results in an increasing trend for absolute benefit in favor of ACE-inhibitors with increasing risk.

ACE-inhibitors on safety outcomes (e.g. cough and angioedema) are slightly decreasing with increasing acute MI risk (Figure 3 and 4). Similar results were observed in the other two databases (see supplementary material).

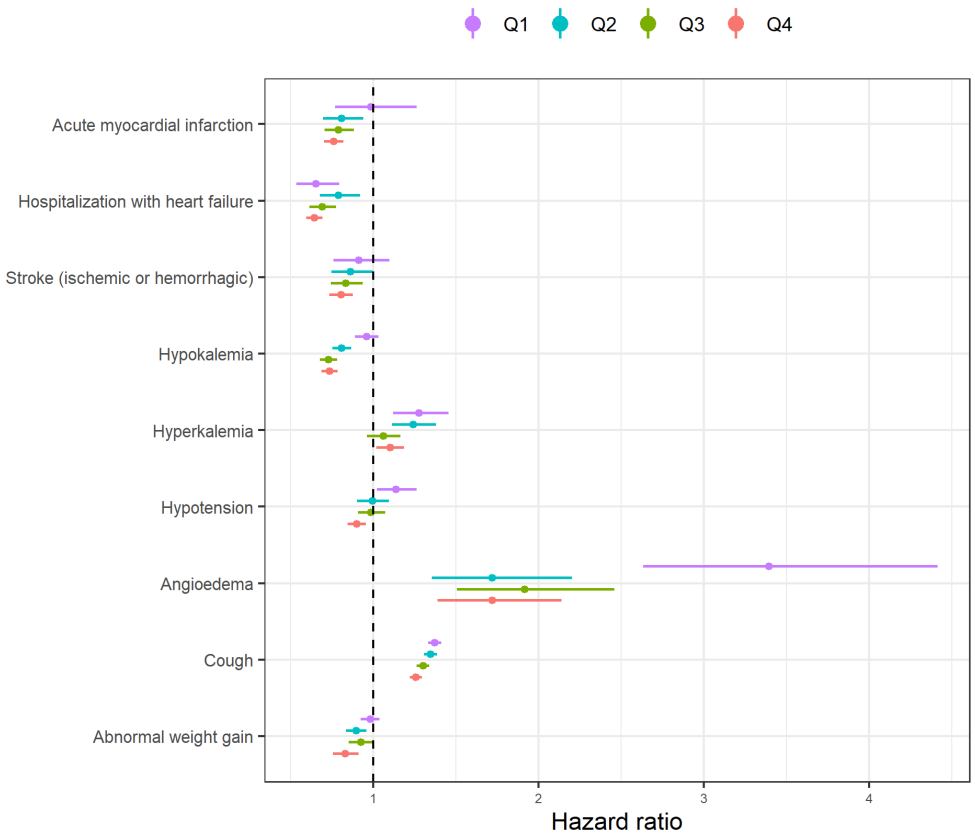

Figure 3: Hazard ratios (relative treatment effects) for the main and safety outcomes, estimated by fitting stratified Cox regression models within quarters of predicted risk of acute myocardial infarction (MI). The four risk quarters (Q1-Q4) are defined using the internally developed model for acute MI

These results suggest that treatment with ACE-inhibitors, compared to treatment with beta blockers, may be focused on the higher risk patients, in whom the benefits outweigh the harms, while beta blockers may be a viable option in lower risk patients, in whom the benefit-harm tradeoff is more favorable. This is in accordance with earlier findings that beta blockers should also be considered as first-line treatment for younger hypertensive patients [23,25]. More thorough evaluation of these results is required in future research, however.

The results of the analyses performed can be accessed and assessed through a publicly available web application (https://data.ohdsi.org/AceBeta9Outcomes).

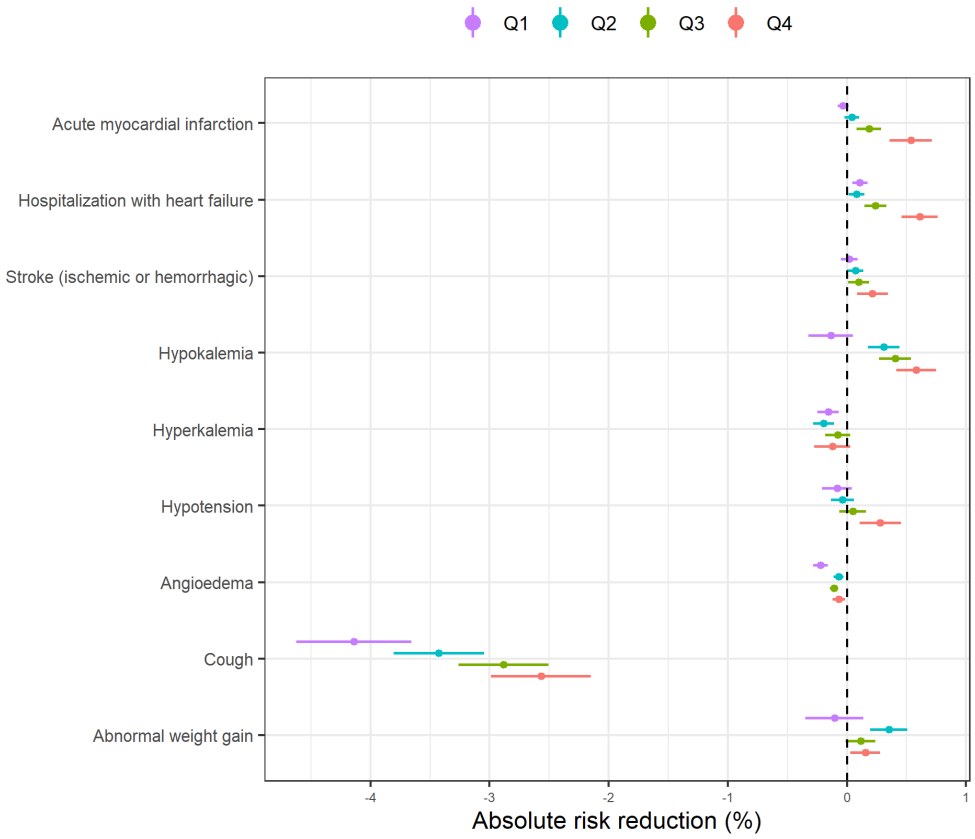

Figure 4: Absolute risk reduction for the main and safety outcomes, estimated by fitting stratified Cox regression models within quarters of predicted risk of acute myocardial infarction (MI). The four risk quarters (Q1-Q4) are defined using the internally developed model for acute MI

4 Discussion

We developed a framework for the assessment of heterogeneity of treatment effect in large observational databases using a risk modeling approach. The framework is implemented in an open source R-package in the OHDSI methods library (https://github.com/OHDSI/RiskStratifiedEstimation). As a proof-of-concept, we used our framework to evaluate heterogeneity of the effect of treatment with ACE-inhibitors compared to beta blockers on 3 efficacy and 6 safety outcomes.

In recent years several methods for the evaluation of treatment effect heterogeneity have been developed in the setting of RCTs [26]. However, low power and restricted prior knowledge on the mechanisms of variation in treatment effect are often inherent in RCTs, which are often adequately powered only for the analysis of the primary outcome. Observational databases contain a large amount of information on treatment assignment and outcomes of interest, while also capturing key patient characteristics. Our framework provides a standardized approach that can be used to leverage available information from these data sources, allowing for large-scale risk-based assessment of treatment effect heterogeneity. Multiple outcomes can be evaluated in patient subgroups of similar baseline outcome risk. Different outcome risk stratification schemes can also be considered. The standardized nature of the framework enables transportability to multiple databases, provided that they are mapped to the OMOP-CDM.

Recently, guidelines on the application of risk modeling approaches for the assessment of heterogeneity of treatment effect in RCT settings have been proposed [27,28]. Our framework aims to translate these guidelines to the observational setting while also providing a toolset for its implementation. Several considerations need to be made. First, estimates may be biased due to the observational nature of the data. We attempt to account for potential confounding by estimating propensity scores within strata of predicted risk. These scores are estimated using regularized logistic regression on a large set of pre-defined covariates. However, such approaches do not account for unobserved confounding [29]. Several sensitivity analyses have been proposed in the literature for measuring the robustness of results in the presence of unobserved confounding. Another approach is to calibrate estimates and confidence intervals based on a large set of negative controls [30,31]. Negative controls are treatment-outcome pairs for which a null effect has been established. Estimating these effects within available data provides an approximation of the null distribution that can be used to empirically recalibrate effect estimates. Future work may extend our framework with this type of analyses.

Our method provides a risk-stratified assessment of treatment effect heterogeneity. However, even though stratification can provide a useful overview for clinical interpretation, these results cannot be applied to individuals in a straightforward manner, as we are still estimating subgroup effects [27]. Presentation of treatment effects

as a continuous function of risk would be more helpful, but is methodologically challenging. Future research is necessary for the development of methods for continuous risk-based assessment of HTE.

Externally derived and well transportable prediction models are preferred for analyzing treatment effect heterogeneity [5]. In the absence of such prediction models, simulations of RCTs have shown that internal models can be used to provide unbiased estimates of treatment effect across the spectrum of baseline risk [16]. However, in observational databases treatment arms may significantly differ in sample size. Because the prediction model will possibly better fit to the larger treatment arm, this may introduce spurious treatment-covariate interactions in the prediction model, leading to sub-optimal risk stratification. As a remedy, we first match the patients in the treatment and the comparator cohorts on the basis of propensity scores. Additionally, we propose to assess model performance in the separate treatment arms to evaluate its aptness for risk stratification.

Our contribution is a translation of the PATH statement principles to the OHDSI methods library [27,28]. Our method encourages open science as it requires accurate definition of the research questions translated into clear and reproducible cohort definitions that can easily be shared among researchers. Our R-package provides a standardized stepwise procedure for the assessment of HTE. This enables source code to be easily shared and evaluated, allowing for reproducible research. Researchers with access to different databases mapped to OMOP-CDM can also very easily extend their overall analyses with risk-based assessment of treatment effect heterogeneity. This enables collaboration among multiple sites with access to different patient populations. We propose that the framework is implemented any time treatment effect estimation in high-dimensional observational data is undertaken.

Recently, disease risk scores have been explored as an alternative to propensity scores for balancing covariates [32,33]. In our method, the objective of risk stratification is not balancing, but assessing the variation of treatment effects on multiple outcomes across patients with different levels of baseline risk. Although using the same risk model for balancing and risk-based HTE analysis may sound attractive, we note that our method only uses one risk model for stratification and one propensity score model for balancing, while separate disease risk score models would be required to analyze treatment effects for each of the multiple outcomes.

In conclusion, the proof-of-concept study demonstrates the feasibility of our framework for risk-based assessment of treatment effect heterogeneity in large observational data. The standardized framework is easily applicable and highly informative whenever treatment effect estimation in high-dimensional observational data is of interest. Our framework is a supplement to the population-level effect estimation framework developed within OHDSI and, in the presence of an adequately discriminating prediction model, can be used to make the overall results more actionable for medical decision making.

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