

# Causal Inference 2: Model-based estimation of causal contrasts

Tuesday, 6 June, 2023

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Statistical Practice in Epidemiology with **R**

2 to 7 June, 2023

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# Outline

- ▶ Causal questions
- ▶ Factual risks and associational contrasts
- ▶ Causal estimands: contrasts of counterfactual quantities
- ▶ Marginal and conditional contrasts, effect among treated, etc.
- ▶ Outcome regression models, standardization or g-formula
- ▶ Exposure modelling, propensity scores and weighting
- ▶ Double robust estimators and machine learning algorithms
- ▶ Time-to-event outcomes: hazards of hazard ratios and estimation of causal contrasts of cumulative risks.

## Some literature

- ▶ Austin & Stuart (2015) *Stat Med* 34(28):3661-3679.
- ▶ Funk et al. (2011) *Am J Epidemiol* 173(7):761-767
- ▶ Hernan & Robins (2020). *Causal Inference: What if?*. CRC Press.
- ▶ Luque Fernandez et al. (2018) *Stat Med* 2018;37(16):2530-2546
- ▶ Schuler & Rose (2017) *Am J Epidemiol* 185(1):65-73.
- ▶ Sjölander (2016) *Eur J Epidemiol* 31:563-574
- ▶ Smith et al. (2022) *Stat Med* 2022;41(2):407-432.
- ▶ Zhou et al. (2022) PSweight vignette.

## Causal question in PECOT format & Example

- P Population:** 2900 women with breast cancer (Rotterdam study)
- E Exposure:** Hormonal treatment (HT)
- C Comparator:** Placebo, no HT
- O Outcome:** Recurrence or death
- T Time frame:** 10 y from surgery to outcome

Causal questions of interest – comparisons of counterfactuals:

- What is the 10-year risk  $\pi^1$  of the outcome, if everybody in P were exposed to HT, as compared with  $\pi^0$ , the risk if nobody were exposed?
- What is the 10-year risk  $\pi_1^1$  of the outcome, among those in P, who are factually exposed to HT, as compared with the risk  $\pi_1^0$ , if they were not exposed?

## Risks by factual exposure and their associational contrasts

- ▶ Let  $Y$  be a binary indicator (1/0) for the outcome to occur within fixed risk period (assuming no censoring, nor competing events), and  $X$  be an exposure variable or risk factor.
- ▶ Let  $\pi_x =$  risk of the outcome to occur during the period in the subset of the target population factually exposed to level  $X = x$ :

$$\pi_x = P\{Y = 1 \mid X = x\} = E(Y \mid X = x).$$

- ▶ For simplicity, let  $X$  be binary, too: exposed vs. unexposed .
- ▶ Common **associational contrasts** of risks between exposure groups:
  - **Risk difference**  $\tau = \pi_1 - \pi_0 = E(Y \mid X = 1) - E(Y \mid X = 0)$ ,
  - **Risk ratio**  $\phi = \pi_1 / \pi_0$ ,
  - **Risk odds ratio**  $\psi = \frac{\omega_1}{\omega_0} = \frac{\pi_1 / (1 - \pi_1)}{\pi_0 / (1 - \pi_0)}$ .

## Conditional associational contrasts

- ▶ The associational quantities above were **marginal**; not conditioned on (or stratified by) any **covariate** – such as sex, age, etc.
- ▶ Let now  $Z$  be a covariate (can be multivariable) and

$$\pi_{xz} = P\{Y = 1 \mid X = x, Z = z\} = E(Y \mid X = x, Z = z)$$

be the risk of outcome during risk period in a population group where both  $X = x$  and  $Z = z$ ,  $x = 0, 1$ .

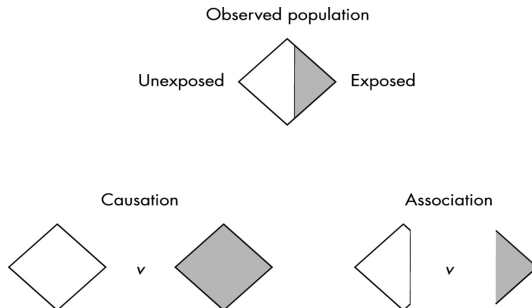
- ▶ Let  $\theta$  be any type of marginal associational contrast, and  $\theta_z$  be the analogous **conditional associational contrast** between exposed and unexposed among those with  $Z = z$ .
- ▶ For instance,  $\tau_z = \pi_{1z} - \pi_{0z}$  is the risk difference conditional on  $Z = z$ , i.e.  **$z$ -specific** risk difference.
- ▶ Similarly  $\phi_z = \pi_{1z}/\pi_{0z}$  and  $\psi_z = \pi_{1z}(1 - \pi_{1z})/[\pi_{0z}(1 - \pi_{0z})]$  are the  **$z$ -specific** risk ratio and odds ratio, respectively.

## Example: Single binary covariate $Z$

- ▶ Let the prevalence of exposure be  $P\{X = 1\} = 0.45$  in the population
- ▶ Let  $P\{Z = 1\} = 1 - P\{Z = 0\} = 0.40$  in the population and  
 $P\{Z = 1|X = 1\} = 0.667$  and  $P\{Z = 1|X = 0\} = 0.182$
- ▶ Let also factual risks  $\pi_{xz} = P\{Y = 1|X = x, Z = z\}$   
by  $X$  and  $Z$  be as shown in the cells of the table below ( $x, z = 0, 1$ )
- ▶ Formula of total probability  $\Rightarrow$  Marginal risks,  $\pi_1, \pi_0$ , contrast  $\tau = \pi_1 - \pi_0$ ,  
and conditional contrasts  $\tau_z = \pi_{1z} - \pi_{0z}$  are as shown in margins:

	$Z = 1$	$Z = 0$	$\pi_x$
$X = 1$	0.50	0.20	$\pi_1 = \mathbf{0.40}$ ( $0.50 \times 0.667 + 0.20 \times 0.333$ )
$X = 0$	0.25	0.10	$\pi_0 = \mathbf{0.13}$ ( $0.25 \times 0.182 + 0.10 \times 0.818$ )
Contrasts	$\tau_1 = 0.25$	$\tau_0 = 0.10$	$\tau = \mathbf{0.27}$

# Associational and causal contrasts



- ▶ **Associational:** Contrast of risks between the **subsets** of the population determined by the subjects' **factual** exposure value.
- ▶ **Causal:** Contrast of risks in the **entire population** under the alternative **potential** or **counterfactual** exposure values; see [Hernan \(2004\)](#), [Hernan & Robins \(2006\)](#), [H&R \(2020\)](#)



## Causal estimands: contrasts of counterfactual risks

- ▶ Let  $Y^{X=x} = Y^x$  indicate (1/0) the event to occur within the risk period, **if** exposure  $X$  were – **counterfactually** – forced to value  $x$  in the whole target population.

- ▶ The **counterfactual** risk if everybody had exposure level  $X = x$

$$\pi^x = P\{Y^{X=x} = 1\} = E(Y^{X=x}).$$

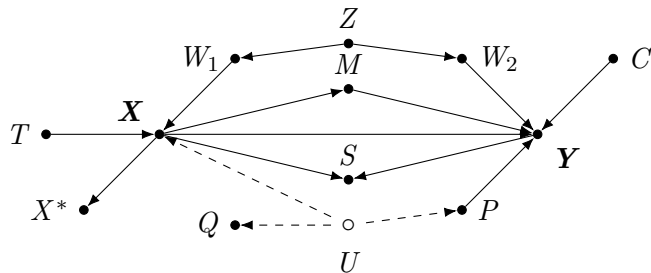
- ▶ **Marginal causal contrasts** of risk

- risk difference (RD)  $\tau^c = \pi^1 - \pi^0 = P\{Y^{X=1} = 1\} - P\{Y^{X=0} = 1\}$ ,
- risk ratio (RR)  $\phi^c = \pi^1 / \pi^0$ ,
- risk odds ratio (OR)  $\psi^c = [\pi^1 / (1 - \pi^1)] / [\pi^0 / (1 - \pi^0)]$ ,

- ▶ Alternative notation: **Judea Pearl's (2010) do-operator**

$$P\{Y = 1 | \text{do}(X = x)\} = P\{Y^{X=x} = 1\}.$$

## Identifying causal contrasts from causal diagram



- ▶ **Causal paths**  $X \rightarrow Y$  and  $X \rightarrow M \rightarrow Y$ : Don't block!
- ▶ **Non-causal paths** between  $X$  and  $Y$ : Block!
  - If already blocked, don't open (e.g. by conditioning on  $S$ ).
- ▶ **Backdoor paths**  $X \leftarrow W_1 \leftarrow Z \rightarrow W_2 \rightarrow Y$  and  $X \leftarrow U \rightarrow P \rightarrow Y$ : Block with minimal effort. – **Sufficient sets**:  $P$  plus one from  $\{Z, W_1, W_2\}$ . – If  $P$  unobserved, substitute by  $Q$ , proxy of  $U$ .
- ▶ No need to adjust for  $T$ . – Adjusting for  $C$  can improve precision.

## Identifying causal contrasts from causal diagram

- ▶ Let  $Z'$  be a set of observed covariates that are **non-descendants** of  $X$
- ▶ If  $Z \subset Z'$  were sufficient to **block** all **open non-causal paths** btw  $X$  and  $Y$ , then counterfactuals are identified by **standardization** – or **g-formula**:

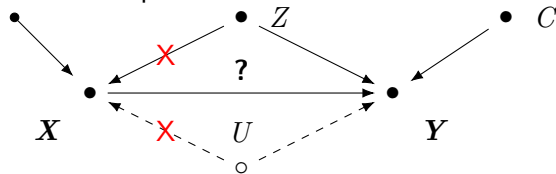
$$\begin{aligned}\pi^x &= E(Y^{X=x}) = E_Z[E_Y(Y|X=x, Z)] \\ &= \sum_z P\{Y=1 \mid X=x, Z=z\}P\{Z=z\}, \quad \text{for discrete } Z.\end{aligned}$$

- ▶ Causal contrasts  $\tau^c$ ,  $\phi^c$ ,  $\psi^c$  are obtained from  $\pi^1$  and  $\pi^0$  thus derived.
- ▶ If there are open paths btw  $X$  and  $Y$ , e.g. via unmeasured confounders  $U$ , the causal contrasts are not identified  $\Leftrightarrow$  **residual confounding**.
- ▶ If  $X$  is **randomized**, then  $X \perp\!\!\!\perp Z \cup U$ , and it holds simply

$$\pi^x = P\{Y^{X=x} = 1\} = P\{Y = 1 \mid X = x\} = \pi_x, \quad \forall x,$$

## Randomized study and causal diagram

$R$  = **Randomization** of exposure



- ▶ When  $X \equiv R$ , no arrow points to  $X$ , and  $X$  is independent of  $Z, U, \dots$ , measured and unmeasured.
- $\Rightarrow$  No confounding!
- $\Rightarrow$  Estimation of causal effect: unadjusted, crude comparison is enough.
- ▶ Precision may be improved by including  $Z$  and  $C$  as covariates.
- ▶ Often realized exposure  $X$  is affected by  $Z$  and  $U$ , thus differing from  $R$ . Then,  $R$  may be utilized as an **instrumental variable**.

## Example (cont'd): Single binary common cause $Z$

- ▶ Causal diagram  $X \rightarrow Y$ ,  $X \leftarrow Z \rightarrow Y$ ; classical confounding triangle.
- ▶ Counterfactual risks (from items on slide 6) obtained by g-formula  $\pi^x = \sum_z \pi_{xz} P\{Z = z\}$  with weights from total population:

$$\pi^1 = 0.50 \times 0.4 + 0.20 \times 0.6 = 0.32,$$

$$\pi^0 = 0.25 \times 0.4 + 0.10 \times 0.6 = 0.16$$

- ▶ Marginal causal contrasts (vs. associational ones)

$$\tau^c = 0.32 - 0.16 = 0.16 \neq 0.27 = 0.40 - 0.13 = \tau,$$

$$\phi^c = 0.32/0.16 = 2 \neq 3.14 = 0.40/0.13 = \phi,$$

$$\psi^c = \frac{0.32/(1 - 0.32)}{0.16/(1 - 0.16)} = 2.47 \neq 4.57 = \psi.$$

- ▶ Associational contrasts were clearly confounded by  $Z$ .

## Conditional causal contrasts

- ▶ With covariate  $Z$ , counterfactual  $z$ -specific risks are defined

$$\pi_z^x = P\{Y^{X=x} = 1 \mid Z = z\}, \quad \text{for all } z \text{ and } x = 0, 1.$$

- ▶ These have their own identifiability conditions.
- ▶ **Conditional** or  **$z$ -specific causal contrasts** of risks are, for instance

$$\tau_z^c = \pi_z^1 - \pi_z^0 = P\{Y^{X=1} = 1 \mid Z = z\} - P\{Y^{X=0} = 1 \mid Z = z\},$$

$$\phi_z^c = \pi_z^1 / \pi_z^0 = P\{Y^{X=1} = 1 \mid Z = z\} / P\{Y^{X=0} = 1 \mid Z = z\}$$

- ▶ If  $\tau_z^c$  has the same value for all  $z$ , the risk difference is **homogenous**. Otherwise it is **heterogenous** or **modified** by  $Z$ .
- ▶ These concepts are defined similarly for risk ratio and odds ratio.
- ▶ Homogeneity of one type of contrast implies heterogeneity of other types.

## Causal contrasts in factual exposure groups

- ▶ Causal risk difference **among exposed** is defined

$$\tau_1^c = P\{Y^{X=1} = 1 \mid X = 1\} - P\{Y^{X=0} = 1 \mid X = 1\},$$

also known as **average treatment effect among treated** (ATT).

– The contrast **among unexposed** (ATU) is analogously defined.

- ▶ The effect often heterogenous, and groups noncomparable.
- ▶ If  $Z$  is a sufficient set, g-formulas for identifying these are

$$\text{ATT} = \pi_1 - \sum \pi_{0z} P\{Z = z \mid X = 1\} = \text{“observed – expected”},$$

$$\text{ATU} = \sum \pi_{1z} P\{Z = z \mid X = 0\} - \pi_0 = \text{“expected – observed”}.$$

- ▶ Different standard populations for ATT, ATU, and for marginal contrast, a.k.a. **average treatment effect in the whole population**:

$$\text{ATE} = \tau^c = \pi^{X=1} - \pi^{X=0} = \sum_z \pi_{1z} P\{Z = z\} - \sum_z \pi_{0z} P\{Z = z\}.$$

## Example: Single binary $Z$ (cont'd)

- ▶  $z$ -specific risks, marginal assoc. & causal contrasts are on slides 6 & 11.
- ▶ For ATT, we have the observed risk  $\pi_1^1 = \pi_1 = \mathbf{0.40}$ , and the expected risk is  $\pi_1^0 = \sum_z \pi_{0z} P\{Z = z | X = 1\} = 0.25 \times 0.667 + 0.10 \times 0.333 = \mathbf{0.20}$ , so  $ATT = 0.40 - 0.20 = \mathbf{0.20}$ .
- ▶ For ATU, the expected risk is  $\pi_0^1 = \sum_z \pi_{1z} P\{Z = z | X = 0\} = 0.50 \times 0.182 + 0.20 \times 0.818 = \mathbf{0.26}$ , and the observed one  $\pi_0^0 = \pi_0 = \mathbf{0.13}$ , and  $ATU = 0.26 - 0.13 = \mathbf{0.13}$ .
- ▶ Here, the causal risk difference is bigger among exposed. – Being exposed seems to be a modifier of the effect of exposure on this scale!
- ▶ Interestingly, the causal risk ratio = 2 is homogenous.

**NB** Popular design for estimating ATT: **matched cohort study**.



## Outcome regression modelling (see lecture on Saturday)

Modelling how expected values, risks, hazards, etc. depend on exposure  $X$  and covariates  $Z$  (modifiers, and/or confounders). – Common elements:

- ▶ Each subject  $i$  ( $i = 1, \dots, N$ ) has an own **profile**, i.e. vector  $(x_i, z_i^\top)$  of values of  $X$  and covariates  $Z$ .
- ▶ In the spirit of **generalized linear models**, let vector  $(\alpha, \beta, \gamma^\top)$  contain regression coefficients, and specify the **linear predictor**  
– assuming so far no **interactions**, nor **effect modifications**

$$\eta_i = \alpha + \beta x_i + \gamma^\top z_i$$

- ▶ **Product terms** can be added for interactions and modifications if needed, and **splines** may be used for continuous covariates.
- ▶ Further model specification depends on the type of outcome variable, causal contrasts of interest, and importance and choice of time scale(s).

# Binary outcome model and classical causal estimation

- ▶ Basic outcome regression model for risks  $\pi$  in fixed risk periods:

$$g\{\pi(x_i)\} = \alpha + \beta x_i + \gamma^\top z_i, \quad i = 1, \dots, N.$$

- ▶ Link  $g(\cdot)$  and causal interpretation of  $\beta$ , assuming the validity of model (including homogeneity or non-modification of the contrast in question) and that  $Z$  blocks all backdoor paths:
  - id  $\Rightarrow \beta =$  risk difference (RD)  $\tau^c$  for  $X = 1$  vs.  $X = 0$ , adjusted for  $Z$
  - log  $\Rightarrow \beta =$  log of risk ratio (RR)  $\phi^c$  – " –
  - logit  $\Rightarrow \beta =$  log of conditional risk odds ratio (OR),  $\psi_z^c$ , – " –**NB.** This is different from marginal OR due to **non-collapsibility**.
- ▶ Random component: Binomial family – Fitting: `glm()`
- ▶ Problems with id & log in keeping predicted  $\hat{\pi}(\cdot)$  between 0 and 1.

## Modern approach: Causal contrasts by g-formula

- Assuming that  $Z$  is sufficient to block non-causal paths, a logistic model is fitted, which may even contain product terms allowing modification

$$\text{logit}(\pi_i) = \log[\pi_i/(1 - \pi_i)] = \alpha + \beta x_i + \gamma^\top z_i + \delta^\top (x_i z_i), \quad i = 1, \dots, n.$$

- For each individual  $i$ , **predicted risks** are computed for both possibilities of exposure:  $X = 0$  and  $X = 1$ , but keeping  $Z = z_i$  as it is

$$\tilde{\pi}_i^{X_i=x} = \text{expit}\{\hat{\alpha} + \hat{\beta}x + \hat{\gamma}^\top z_i + \hat{\delta}^\top (xz_i)\}, \quad x = 0, 1.$$

- Marginal counterfactual risks for  $x = 1, 0$  are estimated applying **g-formula**:

$$\hat{\pi}^{X=x} = \hat{E}_Z[E(Y|X=x, Z)] = \frac{1}{n} \sum \tilde{E}(Y_i|X_i=x, Z=z_i) = \frac{1}{n} \sum \tilde{\pi}_i^{X_i=x}$$

as the data provide a non-parametric estimate of the joint distribution of  $Z$ .

- Estimators marginal causal contrasts** of risks are now, e.g.

$$\hat{\tau}^c = \hat{\pi}^{X=1} - \hat{\pi}^{X=0}, \quad \hat{\psi}^c = [\hat{\pi}^1/(1 - \hat{\pi}^1)]/[\hat{\pi}^0/(1 - \hat{\pi}^0)]$$

## Exposure modelling, propensity scores and weighting

Let  $X$  be a binary exposure variable. Assume again that  $Z$  is a sufficient set

- **Exposure model** predicting individual  $X_i$ :s by confounders is fitted

$$\text{logit}[P\{X_i = 1|Z = z_i\}] = \alpha^* + z_i^T \gamma^*, \quad i = 1, \dots, N.$$

- **Propensity scores**  $PS_i$ , or fitted probabilities of exposure are obtained

$$PS_i = \hat{P}\{X_i = 1|Z = z_i\} = \text{expit}(\hat{\alpha}^* + z_i^T \hat{\gamma}^*).$$

- Individual **weights**  $W_i = w(PS_i, X_i)$  are computed (see next slide).
- Counterfactual risks are estimated as weighted averages of the outcome in the two exposure groups

$$\hat{\pi}^{X=x} = \frac{\sum_{i=1}^n \mathbf{1}_{\{X_i=x\}} W_i Y_i}{\sum_{i=1}^n \mathbf{1}_{\{X_i=x\}} W_i} = \frac{\sum_{X_i=x} W_i Y_i}{\sum_{X_i=x} W_i}, \quad x = 0, 1$$

- From these, marginal causal contrasts are estimated as before.

## Exposure modelling, propensity scores and weighting (cont'd)

- ▶ **Inverse probability weights** (IPW) are used to estimate marginal causal contrasts (like ATE) in the whole population. They are based on inverses of the fitted probabilities of belonging to the realized exposure group:

$$W_i = w(\text{PS}_i, X_i) = \frac{\mathbf{1}_{\{X_i=1\}}}{\text{PS}_i} + \frac{\mathbf{1}_{\{X_i=0\}}}{1 - \text{PS}_i}, \quad i = 1, \dots, n.$$

- ▶ If the interest is on causal contrasts among the treated (like ATT), the **treated weights** are used:

$$W_i = 1 \text{ for } X_i = 1, \text{ and } W_i = \text{PS}_i / (1 - \text{PS}_i) \text{ for } X_i = 0.$$

- ▶ Other: **overlap weights, matching weights, entropy weights**.
- ▶ The goodness-of-fit of the exposure model needs to be assessed. For that purpose, various measures of **covariate balance** are developed.

# Double robust (DR) estimators and machine learning methods

- ▶ The validity of estimator utilizing g-formula or PS-based weighting depends on, how accurately the outcome model or exposure model is specified.
- ▶ **Double robust** (DR) estimation of causal contrasts:  
Combination of g-formula and IPW. – Alternatives
  - **Augmented IPW** (AIPW); see [Jonsson Funk et al. \(2011\)](#),
  - **Targeted maximum likelihood estimation** (TMLE);  
see [Schuler & Rose \(2017\)](#), [Luque-Fernandez et al. \(2018\)](#)

Validity of a DR estimator requires that either the exposure model or the outcome model is correctly specified.

- ▶ Algorithms developed for **supervised learning** increase flexibility in modelling both outcome and exposure (see [Bi et al. 2019](#), [Blakely et al. 2020](#)).

## Interim conclusions

- ▶ Careful specification of causal question and estimands needed.
- ▶ Selection of confounders: efficient blocking of backdoor paths.
- ▶ Basic estimation methods: outcome regression & g-formula, exposure modelling & PS-weighting, double robust estimators.
- ▶ Sufficiently flexible models desirable to reduce misspecification bias.
- ▶ Statistical inference: robust covariance matrix & delta method, bootstrapping, efficient influence curve, etc. – ignored here.
- ▶ We also limited to time-fixed exposure (binary) and confounders.
- ▶ Extensions are available to deal with polytomous exposure as well as time-varying exposure and confounding.

## Time-to-event outcomes: associational hazard quantities

- ▶ Let  $T$  = time to outcome event from a defined zero time, and  $Y(t) = \mathbf{1}_{\{T \leq t\}}$  indicator (1/0) for the outcome to occur by  $t$ .
- ▶ The risk of outcome by  $t$  conditional on exposure level  $x$

$$\pi_x(t) = P\{Y(t) = 1 | X = x\} = P\{T \leq t | X = x\}, \quad x = 0, 1.$$

- ▶ The **hazard** of outcome at  $t$  for those exposed to level  $X = x$  be

$$\lambda_x(t) = \lambda(t | X = x) = \lim_{h \rightarrow 0} \frac{P\{Y(t+h) = 1 | X = x\}/h}{P\{Y(t) = 1 | X = x\}}.$$

- ▶ Common associational contrasts:
  - **Hazard difference**  $\delta(t) = \lambda_1(t) - \lambda_0(t)$ ,
  - **Hazard ratio**  $\rho(t) = \lambda_1(t)/\lambda_0(t)$ .

This is often assumed constant  $\rho$  – as in **Cox regression**.



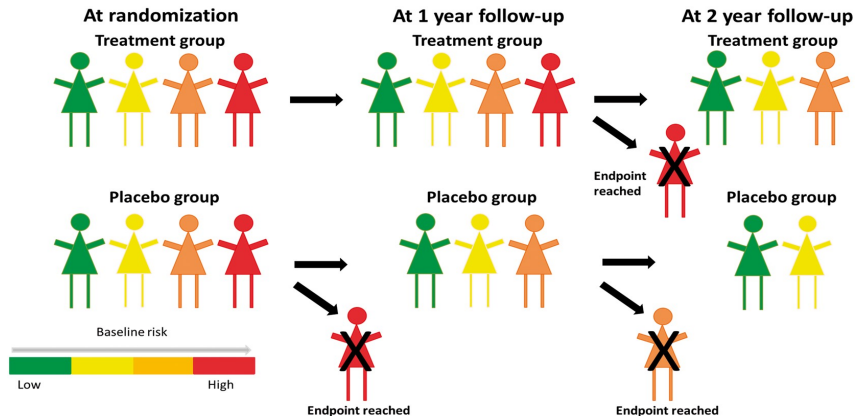
## Causal contrasts of hazards

- ▶ The counterfactual hazard, if everybody were exposed to  $X = x$ :

$$\lambda^x(t) = \lim_{h \rightarrow 0} \frac{1}{h} \frac{P\{Y^{X=x}(t+h) = 1\}}{P\{Y^{X=x}(t) = 0\}}, \quad x = 1, 0.$$

- ▶ Marginal causal contrasts:  
hazard difference (HD)  $\lambda^1(t) - \lambda^0(t)$ , and hazard ratio (HR)  $\lambda^1(t)/\lambda^0(t)$ .
  - ▶ If  $X$  is randomized, these are identified by corresp. assoc. contrasts.
  - ▶ Yet, hazard at any  $t$  is conditional on survival by  $t$ . If  $X$  has any effect,  $Y^1(t) = 0$  and  $Y^0(t) = 0$  imply different populations at risk for  $t > 0$ .
- ⇒ Even if exposure groups were comparable at  $t = 0$ , after that they aren't.
- ▶ Causal interpretation of HR problematic even in a randomized study.

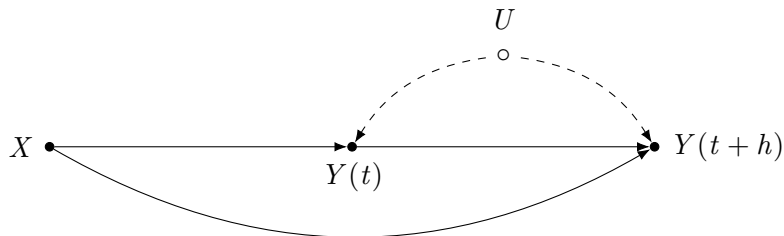
## Example: The exposed have a lower hazard (Stensrud et al 2019)



- In the course of time, the prognostic profile of the remaining exposed group will be worse than that in the remaining unexposed group.

## Hazard of hazard ratios (Hernan 2010, Aalen et al. 2015 )

- ▶ The hazard at any time  $t > 0$  is affected by known and unknown causes of the outcome  $\Rightarrow$  individual **frailty**  $U$  varies in the population.



- ▶  $Y(t)$  is a **collider** on the path from  $X$  to  $Y(t+h)$  via  $U$ .  
Conditioning on  $Y(t) = 0$  opens this non-causal path  $\Rightarrow$  **selection bias**.
- ▶ The observable hazards may behave strangely over time and lead to conclusions like “ $HR > 1$  before  $t^*$  but  $HR < 1$  after that”.

## Example: WHI Trial on MHT and CHD (Manson et al. 2003)

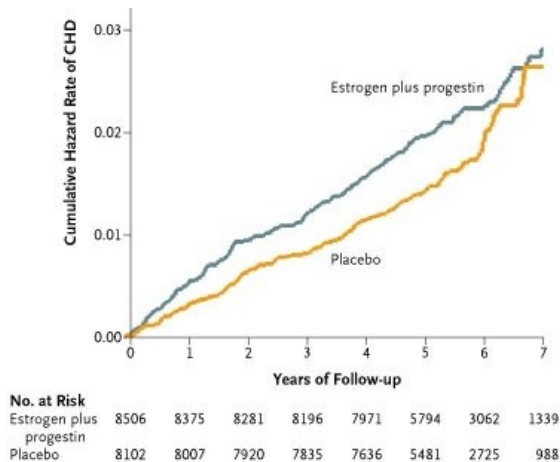
**Table 2.** Estrogen plus Progestin and the Risk of CHD, According to Year of Follow-up.\*

Year of Follow-up	CHD		Hazard Ratio for CHD (95% CI)
	Estrogen-plus-Progestin Group	Placebo Group	
	no. of cases (annualized percentage)		
1	42 (0.50)	23 (0.29)	1.81 (1.09–3.01)
2	38 (0.45)	28 (0.35)	1.34 (0.82–2.18)
3	19 (0.23)	15 (0.19)	1.27 (0.64–2.50)
4	32 (0.39)	25 (0.32)	1.25 (0.74–2.12)
5	29 (0.41)	19 (0.28)	1.45 (0.81–2.59)
≥6	28 (0.37)	37 (0.56)	0.70 (0.42–1.14)

\* CHD includes acute myocardial infarction (MI) necessitating hospitalization, silent myocardial infarction as determined by serial electrocardiography, and death due to CHD. There were nine silent myocardial infarctions (four in the estrogen-plus-progestin group and five in the placebo group). Hazard ratios are stratified according to age, presence or absence of a previous coronary event, and randomly assigned diet modification group and are adjusted for previous coronary-artery bypass grafting or percutaneous transluminal coro-

- ▶ Women, 50-79 y, MHT:  $N_1 = 8506$ , placebo:  $N_0 = 8102$
- ▶ Followed-up for max 8.6 y, mean 5.6 y.
- ▶ Cases & rates/ $10^4$  y  
 $D_1 = 188$ ,  $I_1 = 39$ ,  
 $D_0 = 147$ ,  $I_0 = 33$ .
- ▶ Crude IR = 1.20, adjusted 1.24 (1.00–1.54)

## Example: WHI Trial (cont'd)



- ▶ Curves of cumulative hazard approximate the development of cumulative risks  $\pi_x(t)$  over time.
- ▶ In early years, the curve of MHT runs on top, reflecting higher hazard in that period.
- ▶ By 6-7 year, cumulative risks appear to have reached same level.

## From hazards to causal contrasts of risk

- ▶ A well-specified predictive model for hazards  $\lambda(t|x, z)$  (e.g. Cox or Poisson; suitably flexible) helps, however, to estimate counterfactual cumulative risks  $\pi^1(t)$  and  $\pi^0(t)$ .
- ▶ Suppose  $Z$  blocks all non-causal paths. Then **counterfactual conditional hazards**  $\lambda^x(t|Z = z)$  are identified by observable hazards  $\lambda(t|x, z)$
- ▶ When no competing events exist, counterfactual  $z$ -specific risks  $\pi^x(t|Z = z)$  are identified from factual  $z$ -conditional hazards and risks:

$$\pi^x(t|Z = z) = \pi_x(t|Z = z) = 1 - \exp \left\{ - \int_0^t \lambda(v|x, z) dv \right\}.$$

- ▶ Counterfactual marginal risks are obtained using the g-formula:

$$\pi^x(t) = \sum_z \pi_x(t|Z = z)P\{Z = z\}.$$

# Estimation of causal contrasts from time-to-event data

- ▶ Various methods to estimate counterfactual risks  $\pi^{X=x}(t)$  and their contrasts (see [Denz et al. 2023](#)) – For instance
- (a) Fit a Cox model  $\lambda(t|x_i, z_i) = \lambda_0(t) \exp(\beta x_i + \gamma^T z_i)$ , take estimates of coefficients and baseline cumulative hazard  $\hat{\Lambda}_0(t)$  from which:

$$\tilde{\pi}_i^{X=x}(t) = 1 - \exp\{-\hat{\Lambda}_0(t) \exp(\hat{\beta}x + \hat{\gamma}^T z_i)\}.$$

Counterfactuals  $\pi^{X=x}(t)$  and contrasts are then estimated by g-formula.

- (b) Get weights  $W_i$  from an exposure model, fit Cox with “intercept only” specifying  $X$  as a `strata()` variable and  $W_i$ :s as weights, and estimate  $\hat{\pi}^{X=x}(t)$  using `survfit()`, etc.
- ▶ Other: IPW Kaplan-Meier, use of pseudo-values, DR methods, ...
- ▶ Competing event setting: additional complexities in defining and analysing causal contrasts (see [Rudolph et al. 2020](#), [Young et al. 2020](#)).