The Medical Expansion, Life-Expectancy and Endogenous Directed Technical Change

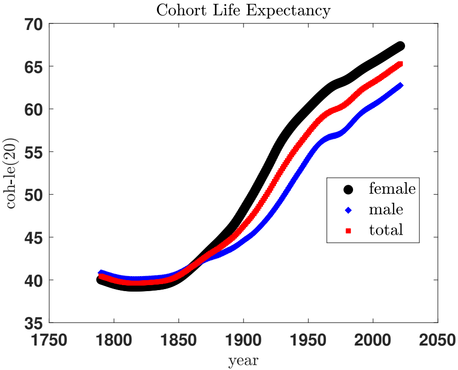
Leon Huetsch   Dirk Krueger
Alexander Ludwig

University of Pennsylvania
University of Pennsylvania, CEPR, CFS, NBER and Netspar
Goethe University Frankfurt, ICIR, CEPR, Pompeu Fabra and Netspar

CERGE-EI Prague

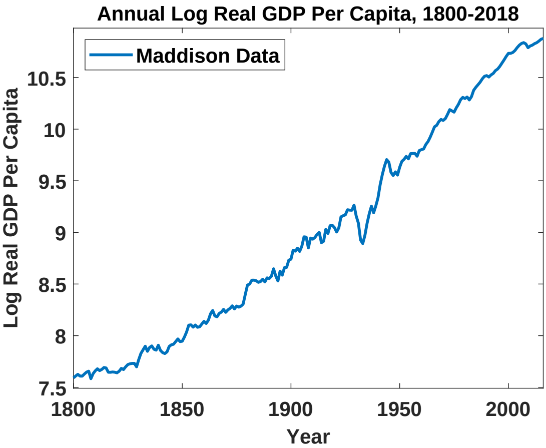
November 2023

Remaining *Cohort* Life Expectancy at Age 20 in U.S.



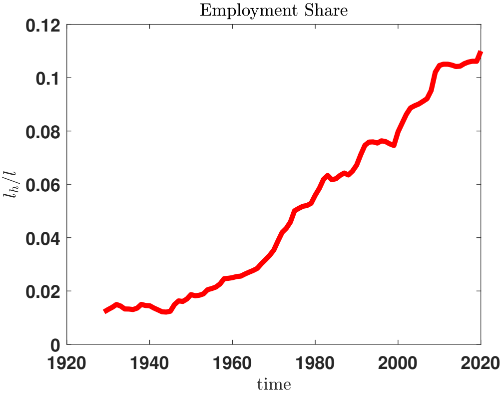
- Flat adult life expectancy at age 20 until about 1840. Then take-off.
- Source: Historical Life Expectancy Data (Haines, Hacker 2010), Human Life-Table Database, Human Mortality Database.

Per Capita Income Growth



- Per capita income (log scale) started increasing in about 1820
- Roughly constant growth at about 2% annually since

Health Employment Share



- Share of workforce employed in health sector ↑ since WW.II.
- Similar trends for health expenditure share and health output share.
- Penicillin first developed in 1929. Widespread use since WW.II

Motivation and Research Objective

- Facts: Three Phases of Health and Medical Development
  1. Life Expectancy at Age 20 flat until about 1840.
  2. Life Expectancy at Age 20 ↑ since about 1840.
  3. Emergence of Modern Health Sector 1920-40: Employment, Output, Expenditure Share ↑
- Objective: Quantitative theory, predict future, evaluate policies
- Building Blocks:
  1. Life Cycle: Diamond (1965)
  2. Endogenous Health Investment & Longevity: Grossman (1972)
  3. Endogenous Directed Technical Change: Aghion & Howitt (1992)

Modeling Approach

- Two-sector OLG model with endogenous technical change:
  - Households:
    - 2-periods lived, endogenous survival to 2nd period.
    - Choices: consumption-savings, health spending.
    - Two health goods: basic hygiene & modern health services.
  - Firms:
    - Two sectors: health goods & final goods
    - Monopolistic competition in intermediate inputs $\Rightarrow$ Profits
    - Endogenous R&D: $\Rightarrow$ higher quality intermediates $\Rightarrow$ Profits.
    - Endogenous income growth through technological $\uparrow$ in both sectors.
- Quantitative implementation: Calibration to initial conditions, broad trends in US data.

Main Mechanism (aka the "Story")

- Phase 1: Low productivity & Low Income $\Rightarrow$ No Health Spending.
- Phase 2: Productivity growth in basic goods sector $\Rightarrow$ Income $\uparrow$

  => Kick-off: Basic health spending $\uparrow$, life expectancy $\uparrow$.
- Phase 3: Further income $\uparrow$ & non-homotheticity in health spending

  => Health spending $\uparrow$

  => Redirection of technological progress to modern health sector.

  => Quality in modern health sector $\uparrow$, price of health goods $\uparrow$.

  => Convergence to interior BGP.

Results Today

- Construction & calibration of simple, illustrative model.
- Calibrated model results: replicate facts quantitatively (sort of).
- Health Policy reforms: not yet.

Related Literature

- Aghion-Howitt meets Grossman meets Diamond

  Diamond (1965), Grossman (1972), Aghion and Howitt (1992, 1998)

- Life expectancy, human capital & technological progress

  Cervellati & Sunde (2005), Hejkal, Ravikumar & Vandenbroucke (2022)

- Normative analyses of optimal health & R&D spending shares

  Hall and Jones (2007), Jones (2004, 2016)

- Reasons for growth of health spending

  Anderson et al. (2003), Fonseca et al. (2013), Zhao (2014), Hollingsworth et al. (2022)

- Health spending, R&D & feedback

  Frankovic and Kuhn (2018a,b), Böhm et al. (2018)

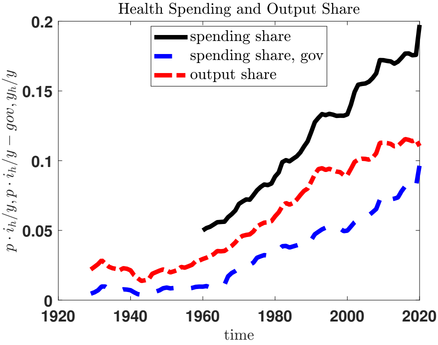
- Demographic change & directed technical change

  Ludwig et al. (2012), Heer & Irmen (2014), Acemoglu & Restrepo (2017, 2021)

Outline

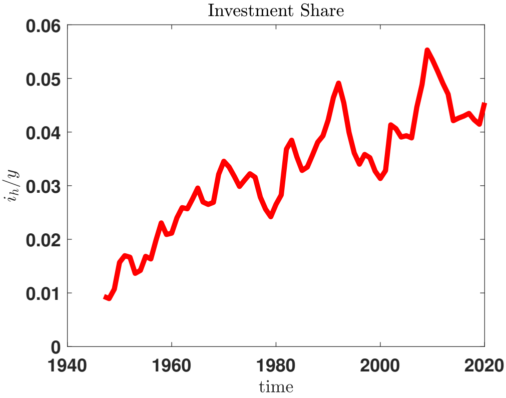
Outline

Health Expenditure & Output Share



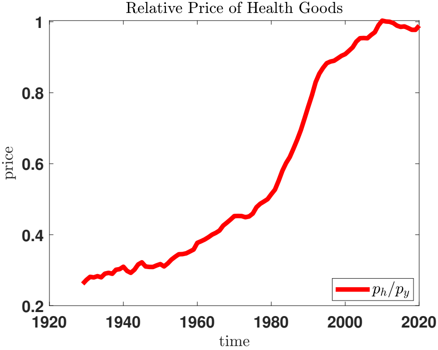
- Health expenditure share ↑
- Output share ↑ since WW.II
- Widespread use of penicillin since WW.II

Investment Share



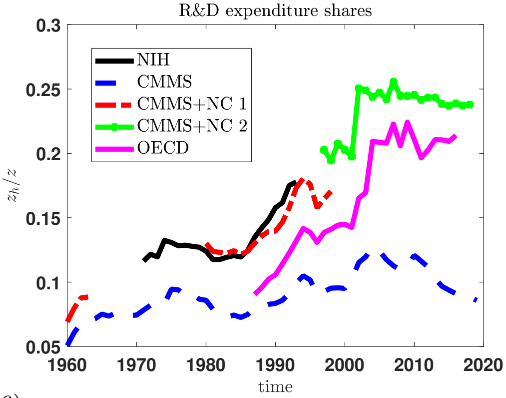
- Investment share ↑
- Data limitation

Relative Price of Health Goods



- Increase of relative price of health goods & services
- Quality adjustment?

R&D Expenditure Share



Source: Jones (2016)

- R&D expenditure share ↑
- Data limitation

Outline

Model: Overview

Two-sector OLG model with endogenous technical change:

- Households:
  - 2-periods lived, endogenous survival to 2nd period.
  - Consumption-savings choice
  - Demand: basic food & hygiene goods & modern health goods.
- Firms and Technology:
  - Two final goods sectors: modern health goods & generic consumption goods (includes hygiene & food).
  - Both sectors: continuum of intermediate inputs. Imperfect substitution & monopolistic competition $\Rightarrow$ Profits
  - Endogenous R&D: $\Rightarrow$ higher quality of intermediates $\Rightarrow$ Profits.
  - Endogenous income growth through quality $\uparrow$ in both sectors.
- SOE: interest rate $R_t = R$ exogenous, constant.

Households: Utility and Choices

- Consumption-savings (c^o_{t+1}, s_t), health investment (i_t, i_{ht}, i_{ft}) given prices p_t, R
- Utility from old-age consumption and survival:

$$\psi(i_t)v(c^o_{t+1}) = \psi(i_t)\left(\frac{(c^o_{t+1})^{1-\sigma}}{1-\sigma} + b\right)$$

- No suicide condition: b sufficiently large (required if $\sigma \geq 1$).
- Survival probability increases in i_t:

$$\psi(i_t) = 1 - (1 + i_t)^{-\xi}.$$

- Health investment quasi-linear in basic, modern health goods:

$$i_t = i_{ht} + (\nu + i_{ft})^{\zeta}$$

- Note that $\psi'(i_{ht} = i_{ft} = 0) < \infty$ but $u'(c_{t+1} = 0) = \infty$.
- Budget constraints:

$$\begin{aligned} c^y_t + p_t i_{ht} + i_{ft} + s_t := e_t + s_t = w_t + T_t := x_t \\ c^o_{t+1} = Rs_t \end{aligned}$$

Analysis of Household Problem: Three Phases

Proposition

Suppose $\frac{x_0}{p_0}$ *is sufficiently low and that the sequence of prices & cash at hand* $\{p_t, x_t\}$ *satisfies:*

$$\frac{x_{t+1}}{p_{t+1}} > \frac{x_t}{p_t}.$$

Then there exist time thresholds $0 < T_1 < T_2 < \infty$ *such that*

1. *Phase 1:* $\forall t < T_1$*:* $i_t = i_{ft} = i_{ht} = 0$, $\psi(i_t) = \psi(0)$
2. *Phase 2:* $\forall t \in [T_1, T_2)$*:* $i_t = i_{ft} > 0$, $i_{ht} = 0$ *&* $\psi(i_t) > \psi(0)$*. Life expectancy* $\uparrow$*: better basic hygiene, no modern health sector.*
3. *Phase 3: For all* $t \geq T_2$ *we have* $i_{ft} > 0$ *&* $i_{ht} > 0$ *as well as* $\psi(i_t) > \psi(0)$*. Life expectancy* $\uparrow$*, also modern health goods* $\uparrow$*.*
4. *BGP w/ constant* $\frac{p \cdot i_h}{x} > 0$, $\frac{i_f}{x} = 0$, $\frac{s}{x} > 0$, $\frac{c}{x} > 0$ *&* $p > 0$.

Production Side: Final Goods Production Firms

- Perfectly competitive final goods producers with CRTS technology in both sectors $j \in \{f, h\}$:

$$y_{jt} = \left(\int_0^1 q_{jit}^{1-\alpha} y_{jit}^{\alpha} \right) l_{jt}^{1-\alpha}$$

- Firms take as given:
  - Quality q_{jit} and prices p_{jit} of intermediate goods
  - Prices of final goods and wages p_{jt}, w_{jt} in sector j.
- Choices: y_{jt}, l_{jt}, y_{jit}
- FOC's for y_{jit} delivers inverse demand function for intermediates:

$$p_{jit} = \alpha p_{jt} \left(\frac{q_{jit} l_{jt}}{y_{jit}} \right)^{1-\alpha}$$

Intermediate Inputs: Monopolistic Competition

- Each variety $i \in [0,1]$ is produced by a monopolist.
- Production function: $y_{jit} = k_{jit}$, full depreciation of capital k_{jit}.
- Firms take as given: inverse demand function & R.
- Profit maximization:

$$\pi_{jit} = \max_{k_{jit}} \left\{ \left[\alpha p_{jt} \left(\frac{q_{jit} l_{jt}}{k_{jit}} \right)^{1-\alpha} \right] k_{jit} - R k_{jit} \right\}$$

- Solution: constant markup over marginal cost R, positive profits:

$$p_{jit} = \frac{1}{\alpha} R > R, \quad \pi_{jit} = \frac{1-\alpha}{\alpha} R k_{jit} > 0$$

Firms: Aggregating the Production Sector

- From intermediate goods producers' FOC: For all $i \in [0, 1]$,

$$\frac{k_{jit}}{q_{jit}} = \frac{k_{jt}}{q_{jt}},$$

where $q_{jt} = \int_0^1 q_{jit} di$ & $k_{jt} = \int_0^1 k_{jit} di$.

- Aggregation in each sector:

$$y_{jt} = k_{jt}^{\alpha} \left(q_{jt} l_{jt}\right)^{1-\alpha}$$

- Distribution of income:

$$p_{jt} y_{jt} = \left[(1-\alpha) + \alpha^2 + \alpha(1-\alpha)\right] p_{jt} y_{jt} = w_t l_{jt} + R k_{jt} + \pi_{jt}$$

R&D Production & Technological Progress

- R&D entrepreneur per variety i: resources z_{jit} on innovation.
- Probability of successful innovation:

$$\phi(z_{jit}; l_{jt}, q_{jit-1}) = \min\left[\varphi\left(\frac{z_{jit}}{\lambda q_{jit-1} l_{jt}}\right)^{\gamma}, 1\right]$$

- Successful innovation: quality improvement $\lambda > 1$ so that $q_{jit} = \lambda q_{jit-1}$.
- Successful innovator: one period monopolist for i: Profits π_{jit}.
- R&D entrepreneur's problem:

$$\max_{z_{jit}} \{\pi_{jit} \cdot \phi(z_{jit}; l_{jt}, q_{jit-1}) - z_{jit}\}$$

  Solution $z_{jit} = \Phi(R, p_{jt})\lambda q_{jit-1} l_{jt}$.

- Varieties i w/ unsuccessful innovations: quality $q_{jit} = q_{jit-1}$, randomly selected entrepreneur eats profits π_{jit}.

Firms: Aggregation of R&D & Economic Growth

- Since $\frac{z_{jit}}{\lambda q_{jit-1} l_{jt}} = \Phi(R, p_{jt})$ constant across i:

$$\mu_{jt} = \varphi \left(\frac{z_{jit}}{\lambda q_{jit-1} l_{jt}} \right)^{\gamma} = \varphi \left(\Phi(R, p_{jt}) \right)^{\gamma}$$

- Quality improvements as engine of growth:

$$q_{jt} = \mu_{jt} \lambda q_{jt-1} + (1 - \mu_{jt}) q_{jt-1}$$

- Growth rate in sector j:

$$g_{jt} = \frac{q_{jt}}{q_{jt-1}} = 1 + (\lambda - 1)\mu_{jt}.$$

Price & Quality of Health Goods

- Good f is the numeraire: $p_{ft} = 1$ for all t.
- Relative price of health goods per health efficiency unit i_{ht}:

$$p_{ht} =: p_t = \left(\frac{q_{ft}}{q_{ht}}\right)^{1-\alpha}$$

- Relative price, per unit of output (non-quality-adjusted):

$$p_t \frac{q_{ht}}{q_{ft}} = \left(\frac{q_{ht}}{q_{ft}}\right)^{\alpha}$$

Balanced Growth Path (BGP) and Transition

- Interior BGP: quality (q_{ft}, q_{ht}), x_t, w_t, T_t grow at rate g.
- Constant prices $R, p_t = p$. Constant shares:

$$\frac{e_t}{x_t} = \frac{p_t i_{ht} + i_{ft}}{x_t} = \frac{p_t i_{ht}}{x_t} = \vartheta, \frac{s_t}{x_t} = 1 - \vartheta, \frac{c_{t+1}}{x_t} = R(1 - \vartheta)$$

- BGP with interior share $\vartheta = \frac{e}{x} \in (0, 1)$ exists iff $\sigma = 1 + \xi$.
- Why? FOC w.r.t. $\vartheta_t = \frac{e_t}{x_t}$ equates marginal benefit of health spending (longer life) to cost (reduced consumption):

$$\max_{\vartheta_t} \left(1 - \frac{1}{(1 + i_t(\vartheta_t x_t))^{\xi}}\right) \left(\frac{(R x_t(1 - \vartheta_t))^{1-\sigma}}{1 - \sigma} + b\right)$$

- For (c_{t+1}, e_t) to grow at same rate: $\sigma = 1 + \xi$.

Transition to BGP

- State of the economy $(q_{ht-1}, q_{ft-1}, n_t, s_{t-1})$
- Given state (& $R_t = R$): static equilibrium, determine p_t (or $\frac{l_{ft}}{l_{ht}}$).
- Assumption $\sigma = 2$, thus $\xi = 1$: closed-form for interior $\vartheta_t \Rightarrow$

  demand for health goods $\Rightarrow$ update of state $\Rightarrow (n_{t+1}, s_t)$.
- Relative price p_t determines $l_{ft}, l_{ht}, \mu_{ft}, \mu_{ht}$.
- Update of state: $\Rightarrow (q_{ht}, q_{ft})$.

Outline

Extensions for Quantitative Analysis

- Utility from consumption also when young (otherwise implausible asset flows):

$$\frac{{c_t^y}^{1-\sigma}}{1-\sigma} + \beta\psi(i_t)\left(\frac{{c_{t+1}^o}^{1-\sigma}}{1-\sigma} + b\right)$$

- Labor intensive health sector: $\alpha_h = 0.22, \alpha_f = 0.33.$ (Acemoglu and Guerrieri 2008).
- Differential improvement factors: λ_j
- Key optimality conditions (& requirement for BGP) qualitatively unchanged (still need $\Rightarrow \sigma = 1 + \xi$). Currently $\sigma = 2$.
- Nonstandard time constraint slows down transition of labor across sectors. Size governed by elasticity ϵ. Currently: $\epsilon = 2$.

$$\left(l_{ft}^{1+\frac{1}{\epsilon}} + l_{ht}^{1+\frac{1}{\epsilon}}\right)^{\frac{1}{1+\frac{1}{\epsilon}}} = 1$$

Questions we Ask of the Model

- Basic Question 1: Can the model replicate basic empirical facts?
  - Life expectancy at age 20
  - Existence & size of modern health sector
  - Relative price of health goods
- 40 year model periods: young 20-59, old 60-99
- 6 periods: 1820 (phase 1), 1860, 1900 (phase 2), 1940, 1980, 2020 (phase 3).
- Question 2: What quantitative role does modern health sector play in expansion of life expectancy.
- (Future) Question 3: (Optimal) role of government in health R&D.

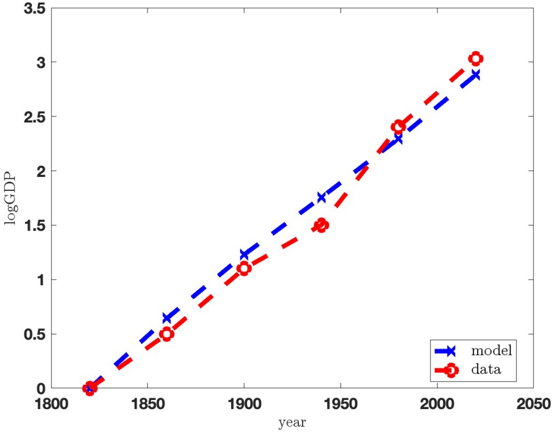
Calibration Strategy

- Broadly: pick parameters to get first two phases and timing of third phase right.
  - Value of life b: kick-off of basic health good spending
  - Initial quality gap: kick-off of modern health good spending
  - Minimum survival probability: adult remaining life expectancy of 40.2 years in 1790.
  - Growth factor λ_f: overall GDP growth
- IES $1/\sigma = 0.5$ standard. $\Rightarrow \xi = 1$.
- Growth factor λ_h: relative growth of modern health sector
- Evaluate the model wrt to performance of third phase.

Parameters

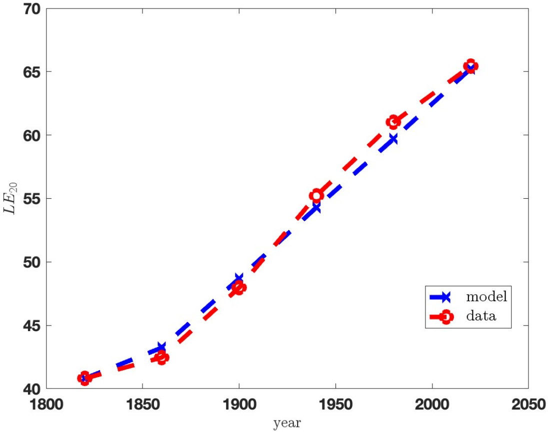
SOE	
Real Rate R-1	1.5 ($\approx$ 1 % annually)
Initial Condition	
Quality gap $\frac{q_{h0}}{q_{f0}}$	0.089
Households	
Discount Factor $\beta/(1-\beta)$	0.085 ($\approx$ 0.94 annually)
Value of Life b	130
IES $1/\sigma$	0.5
Tail parameter, survival function ξ	1
Min. surv. prob. at i = 0, ν^{ζ}	0.021
Scale parameter, modern health investment η	1
Firms	
Capital elasticities $[\alpha_f\ ,\ \alpha_h]$	[0.33,0.2]
Growth factor $[\lambda_f\ ,\ \lambda_h]$	[120,100]
Innovation probability, curvature $[\gamma_f\ ,\ \gamma_h]$	[0.5,0.5]
Innovation probability, scale $[\varphi_f\ ,\ \varphi_h]$	[0.5,0.5]

Comparison to Data: Log GDP per Capita



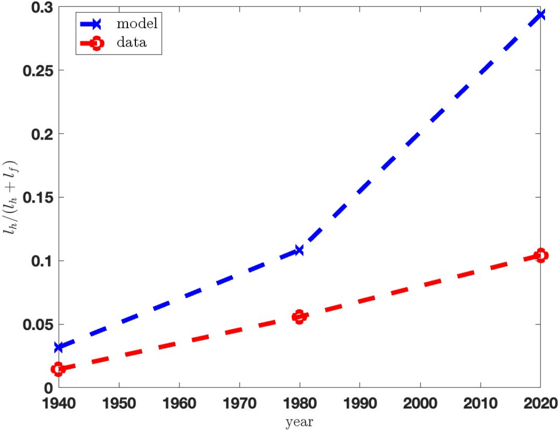
- Comparison looks good (easy to match)

Transition: Life Expectancy at Age 20



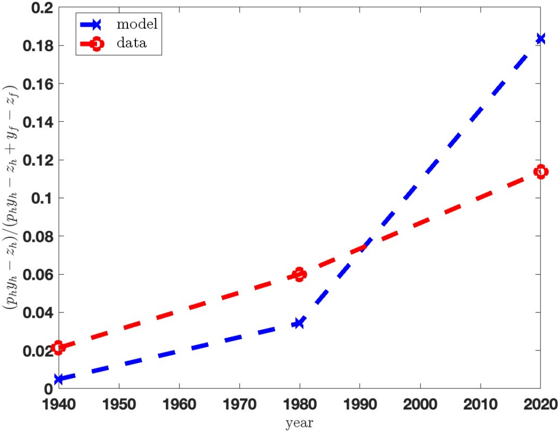
- Constant LE prior to kick-off, then increasing.

Comparison to Data: Health Employment Share



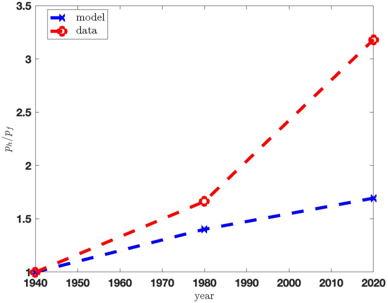
- Matches increase qualitatively, but too rapid quantitatively

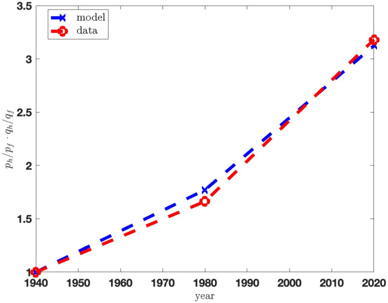
Comparison to Data: Health Output Share



- Matches increase qualitatively, but too rapid quantitatively

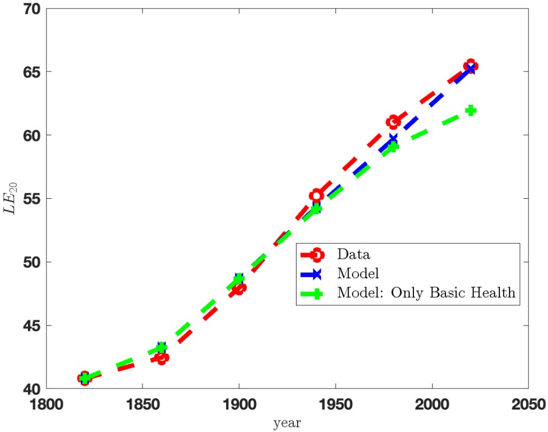
Comparison to Data: Relative Price





- Matches increase qualitatively
- With "re-adjusted" for quality close

Decomposing Life Expectancy at Age 20



- Growing contribution of modern health after 2^{nd} kickoff

Outline

Conclusion: What We Have Done So Far...

Endogenous growth model with a health sector generating...

- ... kick-off of adult life expectancy and (later) modern medicine
- ... positive trend of health spending share
- ... positive trend of health employment, R&D spending shares
- ... increasing relative price of health
- ....continuously increasing life-expectancy in 20-th century

Conclusion: Next Step and Outlook

- Quantitative evaluation: reforms to health care & public R&D policies
- Model elements:
  - Life Cycle Model
  - Explicit model of health accumulation and frailty
  - consumption, savings, health investment, & endogenous retirement
  - household heterogeneity in life expectancy
  - Private & social insurance: health insurance & social security