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Expected Utility Maximization as a Framework for Predicting Vaccine Hesitancy

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Abstract: **A model was developed to predict whether an agent would get vaccinated, incorporating the trade-off between risking death by a disease (COVID-19) and risking severe side effects from the vaccine protecting against the disease. A new utility function was used to circumvent the need for a monetary-based analysis, thereby removing relative healthcare costs as a variable, and so universalizing the model. The model's results majorly aligned with the vaccination risks imposed on specific cohorts (such as young males and myocarditis). The base model excluded coercion, but an extension included it to find that very little coercion is needed to force the agent to get vaccinated.**

Keywords: **behavioral economics, coercion, cost-benefit analysis, COVID-19, healthcare, vaccination.**

1. INTRODUCTION

Vaccine hesitancy is seen as a serious problem by worldwide health officials. The simple reason being that COVID-19 poses a serious threat to the life of many people, and that vaccination is a sure way to reduce the chance of serious illness and death. It is also claimed that the risks incurred after taking a vaccine dose are small. Vaccination reducing the probability of viral spreading is a motivation for vaccine passports being implemented in various countries. Even with a real probability of dying from COVID-19 and the restrictions imposed on the unvaccinated: why do some still refuse to get vaccinated?

As the pandemic continues, it is becoming clearer that the current vaccines (that are designed with reference to the original Wuhan-strain) are progressively losing effectiveness as newer variants evolve. They have limited ability to prevent the spread of the delta-variant, as vaccinated individuals carry similar viral loads as the unvaccinated [1], which shows that total vaccination of every person would not stop the spread of the virus. This is motivated by the recent push for booster shots, as clearly the original 1- or 2-dose course was insufficient. Even more problematic is that the omicron-variant has clear immune-evasion that renders the fully-vaccinated with a susceptibility to infection not statistically different to the susceptibility of the unvaccinated. As for the transmissibility of omicron, the Secondary Attack Rate (SAR) is similar in both cohorts [2].

1.1 Individual Decision-making

Taking the above into account, the choice to take a vaccine becomes more of a personal decision than a decision one makes for the benefit of society. Risk-benefit or cost-benefit analyses in non-financial applications have an issue of weighing the effects of very different circumstances. In financial applications, money (fiat currency) is denominational, so a small effect can be directly compared to a large one in terms of raw dollar amount. In behavioral economics this could be the cost of being hospitalized with COVID-19 versus the cost of being hospitalized with vaccine side effects. But what about comparing death to any of these possibilities? Once dead, an economic agent does not pay for his medical costs, but he would still have a much lower utility being dead than alive and in debt. How can we compare these two possibilities, even if they do not involve dollar-amounts like in the case of publicly-funded healthcare in various countries around the world?

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To many people, being dead is the worst possible outcome, even if there are severe side effects from the vaccine. If the probability of dying from COVID-19 is higher than that of dying from the vaccine then the agent should get vaccinated. Yet, there are still people whom refuse. An interesting thought experiment posed to the reader may help explain the conundrum:

An agent has contracted a rare form of tetanus is his finger. There is no treatment available for the tetanus due to how rare it is. However, the only effect of it is that it causes death with a probability of 1×10^{-100} *%. The only way for him to eliminate this chance of death is to immediately cut off the entirety of the infected finger. There are no other risks incurred after cutting off the finger.*

Death-fearing agents would not choose to risk the rare tetanus as death is worst above all, no matter the cost of losing a finger. Other agents would deem the probability of dying so incredibly low that the possibility could be ignored outright. If the probability were to be raised to 10 %, then one could be certain that the previous refusers would now overwhelmingly opt to lose a finger instead of risking a very likely death.

This thought experiment (as a form of risk-analysis) shows two things: that death and non-monetary injury can be compared to each other (without needing a dollar value to represent each), and that people can change their decision based solely on the chance of death. There should be an additional probability (but was left out to aid simplicity), that cutting off one's finger is not guaranteed, because vaccine side effects are not certain.

Risk-analysis, however, is much more complex than a simple cost-benefit analysis as understood by microeconomic theory. Economic agents always follow some sort of utility curve that has the property of diminishing marginal utility. Most people are typically risk-averse as a result of this, and choose to maximize expected utility (EU). Even if the probability of complications from a vaccine is low, utility can be reduced by such a great amount from these possible complications that remaining unvaccinated would maximize EU. This is possible because the chance of death is reduced by such a small amount (as the chance itself is already so low) that the benefit (added utility) from taking the vaccine pales in comparison to the reduced utility from any negative effects. These negative effects are quite unknown, especially in the long-run, as admitted by the pharmaceutical companies producing these vaccines [3–5].

These considerations are important when it comes to young people. It is agreed upon that young people have little risk from COVID-19, but would bear the brunt of much suffering considering the multiple years left in their lives if there were serious side effects from the vaccines [6]. They would experience a lower utility in the present due to the time-weighted effects of the future. This is not the case for old people much nearer to the average age of life expectancy. Issues concerning fertility and reproductive health further divide the two population segments' propensity to forms of risk.

2. MODELLING

Considering all the above factors, a model is to be developed to predict vaccine hesitancy (preferring to remain unvaccinated) by considering the point at which an agent would be indifferent between taking and not taking the vaccine. This model will compare the expected utility of vaccinating (EU_V) against the expected utility of not vaccinating ($EU_{V'}$). It is assumed that the agent makes a decision without any coercion from external sources.

2.1 Utility Function

Economists typically use an n^{th} root utility function $\left(y = \sqrt[n]{x}\right)$ due to its simplicity in following diminishing marginal utility. Typically, the domain of these functions is some monetary amount that represents consumption (in dollars), while the codomain is the value of utility, where the most logical decision for an agent is to take the option that results in the highest level of utility. For the purposes of modelling a health decision, various properties are required of a candidate utility function $y(x)$, in addition to the fundamental requirement of diminishing marginal utility:

1. To normalize all inputs and outputs to a maximum of unity would mean that all utility-based options can be maximized irrespective of personal wealth and relative healthcare costs.

2. The function must pass through the origin (to represent death having a utility of zero).

3. Small nuisances would hardly decrease an agent's utility very much, so the marginal utility must be horizontal at the maximum utility level.

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4. Conversely, there would have to be extreme circumstances for an agent to be alive yet have similar utility to being dead, so the marginal utility must be vertical at minimum utility.

To summarize mathematically:

Table 1: Utility Function Properties

Property 1	$y(0) = 0$
Property 2	$y(1) = 1$
Property 3	$\lim_{x \to 1^-} \frac{dy(x)}{dx} = 0$
Property 4	$\lim_{x \to 0^+} \frac{dy(x)}{dx} = +\infty$

The n^{th} root utility function fails to conform to all properties, so it cannot be used in modelling (Appendix B, Conjecture 2). In truth, there are an infinite number of utility functions that conform to all properties, but the most simple and logical is the quarter-circle function $y(x) = \sqrt{1 - (x-1)^2}$. This function conforms to all properties (Appendix B, Proposition 1) so can be used. A graphical comparison between the quarter-circle and square-root functions is shown in Fig. 1, but with the traditional input and output quantities of consumption (in dollars) and utility respectively.

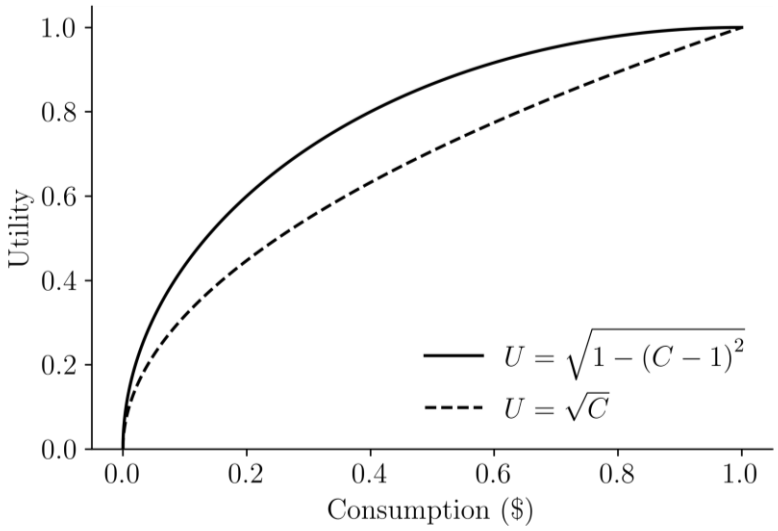

Figure 1: Standard square-root utility function (dashed), and quarter-circle utility function (solid). Where C: consumption ($) and U: utility.

In the place of the dollar-valued input, the non-monetary 'life quality' Λ, where $\Lambda \in [0,1]$, is used instead. Λ is a measurement of quality of life between 0 and 1, where at 1 the agent is perfectly content with the circumstances of his life, and at 0 the agent is dead. A real number between 0 and 1 shows by what percentage the agent's life is defective $(1 - \Lambda)$. Additionally, it respects the fact that any agent could suffer from various conditions within his life that do not affect his total utility very much (as a consequence of Property 3). For example, the agent could be suffering from a condition that decreases his life quality to $\Lambda = 0.8$, however $U(0.8) \approx 0.9798$ which is still very close to 1. For the agent's utility to become very low would require him to suffer an extreme, chronic, or disabling trauma (as a result of Property 4). For posterity, the parent set of Λ can be extended to $\mathbb{R}$. There is no real meaning for a negative life quality, or having $\Lambda > 1$, but there could be some future nuance currently unnoticed. So for this paper's purposes, the agent cannot

have a negative life quality, then $U(\Lambda < 0) = 0$, and the agent cannot have more than the maximum quality of life (1 or 100 %) so $U(\Lambda > 1) = 1$, which gives Eqn. (1):

$$U(\Lambda) = \begin{cases} \sqrt{1-(\Lambda-1)^2} & \text{if } \Lambda \in [0,1] \\ 1 & \text{if } \Lambda > 0 \\ 0 & \text{if } \Lambda < 1 \end{cases} \quad (1)$$

2.2 Probability of Death From COVID-19

The probability of death depends on multiple variables, namely age, sex and health status. A June 2020 study from Stockholm University determined the probabilities dependent on these variables (Table 2).

A Freedom Of Information (FOI) request was granted in the UK, which gave the number of people that died from COVID-19 that had no prior conditions (Table 3). Other sources for data on comorbidities affecting COVID-19 deaths were unable to be found, other than a self-check tool developed by Oxford University called the QCovid risk calculator *(Copyright © 2021, Oxford University Innovation Limited)*. An individual is able to input his own health conditions into the tool and produce two probabilities: being hospitalized from COVID-19, and dying from COVID-19. The FOI-granted data give a 19-year-old male a 99.99984 % chance of surviving a COVID-19 infection, while the QCovid tool gives a probability of 99.99990 %; showing close agreement (less than 6×10^{-5} % difference).

Statistics can be found elsewhere for each individual country, but often it is difficult to separate the variables, which results in a blanket death probability for each age range (no consideration of prior conditions affecting death). The death probabilities across entire age ranges were computed for Canada, Germany, Japan, USA and Italy from first-hand available data. These figures serve as a comparison to the Stockholm and UK data (Table 4).

Table 2: Stockholm University study on COVID-19 survivability by age, sex and comorbidities [7]

Age	Female		Male	
	No underlying conditions (%)	One or more conditions (%)	No underlying conditions (%)	One or more conditions (%)
0–19	99.99996	99.9639	99.99996	99.9603
20–29	99.9998	99.9466	99.9997	99.9037
30–39	99.9991	99.8636	99.9986	99.7900
40–49	99.9980	99.8153	99.9965	99.6943
50–59	99.9888	99.3647	99.9815	99.2135
60–69	99.9562	98.7605	99.8895	97.9992
70–79	99.8251	97.6094	99.5245	95.6517
80+	98.9087	92.8152	96.3318	79.9154

Table 3: UK COVID-19 survivability, by age and comorbidities [8, 9]

Age	Entire age range (%)	No underlying conditions (%)
0–19	99.9991	99.99984
20–29	99.9979	99.99932
30–39	99.9926	99.99854
40–49	99.9772	99.99784
50–59	99.9341	99.99219
60–69	99.8071	99.98504
70–79	99.4461	99.96685
80+	97.6239	99.852

Consult Table A1 in Appendix A for the raw data.

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Table 3: COVID-19 survivability based on age, according to country [10–21]

Age	Survivability (%)				
	Canada[1]	Germany[2]	Japan[3]	USA[4]	Italy[5]
0–19	99.9946	99.9939	100.0	99.99019	99.98258
20–29	99.97623	99.97819	99.99608	99.95441	99.97756
30–39	99.93685	99.96927	99.98083	99.82349	99.95548
40–49	99.83623	99.90185	99.93421	99.49311	99.84124
50–59	99.45743	99.57565	99.78718	98.23295	99.40253
60–69	97.75585	97.72065	98.81702	93.66716	97.27383
70–79	91.05204	89.70307	95.35934	85.18149	90.82062
80+	75.79945	79.39385	86.8473	71.68954	78.32647

[1] Raw data for Canada in Table A2.
[2] Raw data for Germany in Table A3.
[3] Raw data for Japan in Table A4.
[4] Raw data for the USA in Table A5.
[5] Raw data for Italy in Table A6.

It must be noted that the conditions for 'death from COVID-19' varies by country, which can explain some of the variability in death probabilities. The UK data is perhaps too optimistic as 80+ year-olds with some or no health conditions have a probability of dying from COVID-19 at ~2.5 %, while this same age group in the USA have a ~19.5 % probability of death. If these older age-groups are ignored for all data sets, it can be seen that the survivability for young people is consistently high. Japan for instance has not recorded a single death for people in the 0–19 age range. This same age range has an average survivability of over 99.99 % across the other four countries, including any or no comorbidities. Without any negative health conditions, the survivability is over 99.999 %.

2.3 Long-term Negative Effects

2.3.1 COVID-19

There are some long-term effects of a serious COVID-19 infection. Most people suffering from "long COVID" were old or immunocompromised before infection, the same group of people experiencing death from the disease [22]. Of the numbers available, 10–20 % of people that recovered from the disease still had lingering fatigue or loss of smell 6 months later, irrespective of having suffered a mild or severe infection [23]. These long-term effects are mild, and likely impact a person's utility very marginally. The other much more rarer effects, such as heart inflammation, are the typical effects that could be said to impact someone's utility to a very great extent (as heart damage is permanent). However, these serious effects are not common amongst the young and healthy after contracting COVID-19 (7 per million for myocarditis due to COVID-19 infection) [24]. A study popular in the press gave a myocarditis incidence rate of 450 per million from COVID-19 infection, but this study contains glaring errors that result in it being rejected (Appendix C).

2.3.2 COVID-19 vaccines

As described previously, the current COVID-19 vaccines have unknown long-term risks. However, during the phase III clinical trials of the Pfizer and Moderna vaccines (that are still ongoing until 2023), 7 in 35,654 trial participants contracted some form of facial paralysis (probability of roughly 0.0196 %) [25]. In June 2021 the FDA added heart inflammation warnings to the Pfizer and Moderna vaccine fact-sheets [26]. The risk for myocarditis from one of the COVID-19 vaccines is similar to the risk after contracting the disease itself. However, this is not true for men and boys under 40, as the rate can be as high as 101 per million (0.0101 %) compared to a rate of 7 per million for COVID-19 [24]. A similar rate has been reported in Israel at 106.9 per million (0.01069 %) [27], while a study found a rate double this at 195 per million for 12–17 year-old boys [28].

It has been recently confirmed that there are some menstrual changes incurred following two doses of a COVID-19 vaccine. However, it is claimed that these effects are not serious and only short-lived [29], but they do ignite worries over fertility.

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It should be noted that many of these side effect probabilities are higher than the death probabilities for young and healthy people — as recorded in Section 2.2.

2.3.3 Previous vaccines and pharmaceutical liability

The last major pandemic, H1N1 Swine Flu, fizzled out before the new vaccines became widely-used. One of these vaccines, Pandemrix, caused narcolepsy in 4.333×10^{-3} % of people that took it — but primarily children and adolescents. Pandemrix had an adverse-event rate 7 times that of other similar vaccines — combined. These figures, dating from 2009–2010, only came to light during the discovery process of a lawsuit lodged against the vaccine manufacturer GlaxoSmithKline (GSK). These risks were quantifiable during vaccine administration, yet no vaccinees were informed of them [30].

Still today no one knows why Pandemrix had these issues. There were early concerns over its use of an adjuvant that boosted its effectiveness. Arepanrix however — another GSK vaccine against H1N1 — also contained this adjuvant, while GSK's third vaccine (without a name) did not contain the adjuvant. These last two had similar and much lower levels of risk as compared to Pandemrix. A possible explanation is that manufacturing faults impacted Pandemrix alone, because both it and Arepanrix are the exact same vaccines but manufactured in different facilities [30].

Worldwide, vaccine manufacturers are given indemnity from damages in the event of a pandemic. This is to fast-track the development and administration of vaccines [30]. In the case of COVID-19, manufacturers such as Pfizer have forced strict clauses in their vaccine contracts with countries. Leaked documents show that Pfizer tried to have Brazil and Argentina collateralize sovereign assets to secure their indemnity [31]. These manufacturers have no incentive to ensure that their vaccines are not rushed before long-term safety data is available. The most prominent example being the aforementioned Pandemrix.

2.3.4 Vaccine-enhanced disease

Cold- and flu-directed vaccines have been notoriously plagued with issues, mostly due to the rapid rate of mutation. Successful coronavirus vaccines have not been brought to market until COVID-19. There are many concerns over vaccinating against such a highly mutable virus during a pandemic, when the virus has the highest ability to mutate with the large number of infections.

One concern is antibody-dependent enhancement (ADE), which can result in a more infectious or virulent virus as it has evolved to use the body's existing defenses against itself. A mechanism for ADE has been shown in vitro concerning the delta-variant, which is possible because the original Wuhan-strain is long extinct but has seen continued use as an antigen-source in the COVID-19 vaccines [32].

Another concern is original antigenic sin (OAS), especially in relation to the continued use of booster doses. Each consecutive booster would have a diminishing effect on the body's antibody levels, and could hamper the immune system's ability to produce antibodies for later variants and variant-specific vaccines.

2.4 Expected Utility

The expected utility of an action is found by the summation of all probabilities pertaining to this action, whereby each is multiplied by its respective utility if such an outcome were to occur. The action to *not* take the vaccine incurs with it the possibility of death ($\Lambda = 0$), and the possibility of life, after contracting COVID-19:

$$\begin{aligned} \mathrm{EU}_{\mathrm{V}'} &= \mathrm{P}(\mathrm{D}|\mathrm{V}') \cdot \mathrm{U}(0) + \mathrm{P}(\mathrm{D}'|\mathrm{V}') \cdot \mathrm{U}(\Lambda) \\ \therefore \mathrm{EU}_{\mathrm{V}'} &= \mathrm{P}(\mathrm{D}'|\mathrm{V}') \cdot \mathrm{U}(\Lambda) \end{aligned} \tag{2}$$

Where D denotes death, D′ denotes life, V denotes being vaccinated, V′ denotes not being vaccinated, $\mathrm{EU}_{\mathrm{V}'}$ is the expected utility of not vaccinating, $\mathrm{P}(\mathrm{D}|\mathrm{V}')$ is the probability of death given not vaccinating, and $\mathrm{P}(\mathrm{D}|\mathrm{V})$ is the probability of life given not vaccinating.

The action to take the vaccine incurs with it not only the risk of death and life from contracting COVID-19, but also the risk of side effects. This results in a 'true' probability of life that includes the probability of side effects:

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$$P_{true}(D'|V) \equiv P(D'|V) \cdot P(S') + P(D'|V) \cdot P(S) \tag{3}$$

Where S denotes suffering from side effects, S' denotes no side effects being experienced, $P(S)$ is the probability of suffering side effects, and $P(S')$ is the probability of not experiencing side effects.

The life quality from experiencing side effects will be represented by Λ_S, where $0 < \Lambda_S < \Lambda$. This, in addition to Expr. (3), allows formulating the expected utility of taking the vaccine:

$$\begin{aligned} EU_V &= P(D|\,V) \cdot U(0) + P(D'|\,V) \cdot P(S') \cdot U(\Lambda) + P(D'|\,V) \cdot P(S) \cdot U(\Lambda_S) \\ \therefore EU_V &= P(D'|V) \cdot P(S') \cdot U(\Lambda) + P(D'|V) \cdot P(S) \cdot U(\Lambda_S) \end{aligned} \tag{4}$$

2.5 Vaccine Effectiveness

According to the WHO, a vaccine's effectiveness is the degree to which it prevents infection in the real world (not in a controlled environment) [33]. However, this paper's modelling was done with reference to death caused by COVID-19, not infection. The 'effectiveness at reducing death' of the vaccines is reportedly as high as 90–91 % after the second dose of vaccination across all age groups and vaccines [34].

The effectiveness will be included in the model by having it reduce the chance of death by some ε, which allows relating the life probabilities from taking and not taking the vaccine:

$$p = r + \varepsilon\,(1 - r) \tag{5}$$

and solving for r:

$$r = \frac{p - \varepsilon}{1 - \varepsilon} \tag{6}$$

Where $p \equiv P(D'|V)$ and $r \equiv P(D'|V')$.

Remark 1. If an agent has a chance of life prior to being vaccinated of $r = 0.95$ and he takes a vaccine with effectiveness $\varepsilon = 0.75$, then his chance of life post-vaccination is $p = 0.95 + 0.75 \cdot (1 - 0.95) = 0.9875$.

2.6 Combined Models

Combining Eqns. (2, 4–6) and setting $q \equiv P(S)$ for sake of brevity:

$$EU_V = p\,(1 - q)\,U(\Lambda) + p\,q\,U(\Lambda_S) \tag{7}$$

$$EU_{V'} = \frac{p - \varepsilon}{1 - \varepsilon}\,U(\Lambda) \tag{8}$$

2.7 Indifference Model

The above EU models can each be computed for an individual agent, and the agent's most rational decision is to take the action that maximizes EU. A more succinct (and economist-oriented) method is to determine the level at which the agent is *indifferent* between taking and not taking the vaccine by equating the two models:

$$EU_V = EU_{V'}$$

or,

$$p\,(1 - q)\,U(\Lambda) + p\,q\,U(\Lambda_S) = \frac{p - \varepsilon}{1 - \varepsilon}\,U(\Lambda) \tag{9}$$

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The indifference model depends on 5 variables: p, q, Λ, Λ_S and ε. If 4 can either be determined from available statistics or estimated using logical reasoning, then the 5th variable can be solved for algebraically. Solving for p:

$$p\,(1-q)\,U(\Lambda) + p\,q\,U(\Lambda_S) = \frac{1}{1-\varepsilon}\left(p\,U(\Lambda) - \varepsilon\,U(\Lambda)\right)$$

$$(1-q) + q\frac{U(\Lambda_S)}{U(\Lambda)} = \frac{1}{1-\varepsilon} - \frac{\varepsilon}{p\,(1-\varepsilon)}$$

$$\frac{\varepsilon}{p\,(1-\varepsilon)} = (q-1) - q\frac{U(\Lambda_S)}{U(\Lambda)} + \frac{1}{1-\varepsilon}$$

$$\therefore p = \frac{\varepsilon}{(q-1)\,(1-\varepsilon) - q\,(1-\varepsilon)\,\frac{U(\Lambda_S)}{U(\Lambda)} + 1} \tag{10}$$

then arranging for r^* by Eqn. (5) and defining the life-utility ratio $u_\lambda \equiv \frac{U(\Lambda_S)}{U(\Lambda)}$:

$$r^* = \frac{\varepsilon\,(qu_\lambda - q + 1)}{\varepsilon q u_\lambda - \varepsilon q + \varepsilon - q u_\lambda + q} \tag{11}$$

This probability r^* is defined as the point at which the agent would be indifferent between choosing to vaccinate and choosing to not, where r is the pre-vaccine probability of surviving a COVID-19 infection. If the agent were to know his own r (potentially from the data presented in Section 2.2) then he can know his most logical decision concerning vaccination (Table 5).

Table 5: Outcome of decision to vaccinate or not dependent on r and r^*

Condition	Outcome	*EU* Status
$r < r^*$	Choose to vaccinate	$EU_V > EU_{V'}$
$r = r^*$	Indifferent between being and not being vaccinated	$EU_V = EU_{V'}$
$r > r^*$	Choose to not vaccinate	$EU_V < EU_{V'}$

Additionally, solving for q^*:

$$q^* = \frac{\varepsilon\,(1-r)}{\varepsilon r u_\lambda - \varepsilon r - \varepsilon u_\lambda + \varepsilon - r u_\lambda + r} \tag{12}$$

Where q^* is the probability of side effects from taking a vaccine, at the point at which the agent is indifferent between taking and not taking a vaccine. As the true probability q of side effects is unknown, the agent must make a decision for himself as to how large a risk of side effects he is willing to accept. The agent could also make use of the currently available side effect statistics as put forth in Section 2.3.2.

3. MODEL APPLICATIONS

The developed model must be applied to situations where individuals make health decisions. Some variables of the model need to be reasoned for, as relevant statistics are not available. From a logical approach, Λ can be set to 1, as most people likely have a very full life quality as it is. Setting Λ to 1 can also be thought of as a 'reference' point that side effects can be compared to. This is useful as the life quality experienced after contracting a side effect would be in relation to the original reference life quality. For example, setting Λ_S to 0.75 implies a 25 % deduction in life quality.

3.1 Approximating Λ_S

The most appropriate method in approximating Λ_S is to relate it directly to the side effect in question.

3.1.1 Λ_S for myocarditis

Heart inflammation research is a relatively young field, and this comes with the issue of poor screening methods and drug treatment. The imaging and testing methods to determine if myocarditis is present are prone to false negatives and under-diagnosis. Additionally, if inflammatory cardiomyopathy (ICM) is present instead of myocarditis, then there is no current clinical method to determine a prognosis. ICM is worrisome because it may have developed from undiagnosed myocarditis as a result of autoimmunity [35]. Elevated troponin levels can be used to diagnose the severity of forms of heart inflammation, but there is no data available on the troponin levels of COVID-19 vaccine-induced myocarditis patients, so calling the condition 'mild' is premature.

Treatment for myocarditis is varied. Patients must typically abstain from any activities that can raise the heart rate so as to prevent any further cardiac damage [36]. Immunosuppressants and antivirals are usually prescribed for viral myocarditis [35], but these come with the issue of needing to take them for multiple years and deal with their side effects. Immunosuppressive drugs specifically can cause muscular and skeletal degradation [37]. If forms of arrhythmia are present, then further specialized drugs are required, in addition to the possibility of also needing an implantable cardioverter-defibrillator (ICD) [35].

The mortality rates of myocarditis are varied, but usually are poor within 5 years for severe forms [38]. If myocarditis does not disappear (active myocarditis), then there is a mortality rate between 25 % and 56 % from 3 to 10 years [39]. Even if the myocarditis resolves itself, the possibility for sudden cardiac death (SCD) persists [40], wherein amongst young people acute myocarditis results in 10 % of all deaths from SCD [35].

Considering the high probability of death, the likelihood of needing to take copious drugs for many years, the requirement to abstain from the pharmacological benefits of exercise for multiple months, the plausible future need for intrusive electronic implants, and the possibility that the myocarditis *may* in fact be 'mild' and disappear on its own: Λ_S was set to 50 % for myocarditis side effects. The probability of the myocarditis being 'mild' is unknown in terms of the COVID-19 vaccines, but could be a significant percent. If it is *not* 'mild' then it is likely to be deadly in only a few years, so this Λ_S value is considered conservative but reasonable taking into account the above analysis.

3.1.2 Λ_S for narcolepsy

Narcolepsy happened during the H1N1 pandemic, and not COVID-19. However, it serves as another example to validate the developed model as the issues that plagued Pandemrix could just as easily happen with the COVID-19 vaccines (with similar severity and probability). Narcolepsy is known to be caused by an autoimmune response that permanently destroys sleep-regulating neurons, hence why a vaccine with issues can cause a 12-fold increase in diagnosed narcolepsy cases (Pandemrix) [30, 41].

Narcolepsy is a chronic condition (never cured) that can only be managed with strict sleep and napping schedules in addition to a drug cocktail taken in the morning and throughout the day [42]. The most severe effect of narcolepsy is cataplexy wherein complete or partial paralysis is endured for multiple minutes. During this time-frame, an agent on his own or driving a vehicle could be put into a variety of life-threatening situations. Type 1 narcolepsy is the only type that causes cataplexy, but this is also the only type caused by an autoimmune response (for example with vaccinal aetiology), so agents that develop narcolepsy from a vaccine will have cataplexy [41, 43].

Enduring cataplexy means that driving must be eliminated entirely or confined to brief periods of time while taking a variety of stimulants. Cataplexy is "most often [caused] by positive emotions such as those associated with laughing at a joke or unexpectedly encountering a friend" [41], which means that an agent's life quality is diminished by a large amount by having to restrict his enjoyment of life. Disturbing hallucinations can also happen during cataplexy. Additionally, excessive weight gain and depression are all common with narcolepsy, where each involve more medication and therapy to treat [41].

Hence, Λ_S for a narcolepsy side effect was set to 25 %. This is in accordance with the fact that: narcolepsy is permanent, narcolepsy from a vaccine will be type 1 (involving cataplexy), multiple drugs are required for continual treatment, high-

concentration activities and jobs like driving or piloting aircraft need to be eliminated or reduced, and finally the social joys of life may need to be restricted to prevent cataplexy episodes. Thus, this Λ_S value is considered appropriate.

3.2 Worked Examples

The following examples all make use of the given COVID-19 death (Section 2.2) and vaccine side effect statistics (Sections 2.3.2 and 2.3.3).

Example 1. An agent's probability of contracting myocarditis after two doses of a COVID-19 vaccine is set at 101 per million ($q = 1.01 \times 10^{-4}$), and his life quality with myocarditis is 50 % ($\Lambda_S = 0.5$). The effectiveness of the vaccine at preventing his death from the targeted disease is 91 % ($\varepsilon = 0.91$). The agent follows a quarter-circle utility function. Will the agent choose to get vaccinated?

Ans. Using Eqn. (11),

$$r^* = \frac{0.91 \cdot \left(1.01 \times 10^{-4} \cdot \frac{U(0.5)}{U(1)} + 0.999899\right)}{9.191 \times 10^{-5} \cdot \frac{U(0.5)}{U(1)} - 1.01 \times 10^{-4} \cdot \frac{U(0.5)}{U(1)} + 0.91000909}$$

$r^* \approx 99.99851\ \%$

The given q value is specifically for men and boys under 40, but allow us to assume it applies universally. If the calculated r^* value is looked up in either the Stockholm data (Table 2) or the UK data (Table 3), then all men with no underlying conditions below the 40–49 age range will choose to *not* get vaccinated. The agents most affected by the increased risk of myocarditis coincides with those agents that will choose to not get vaccinated. The risk is not worth it on the basis of utility.

Example 2. Given: $q = 0.01$, $\Lambda = 1$, $\Lambda_S = 0.1$ and $\varepsilon = 0.5$. How will the agent choose to vaccinate dependent on r?

Ans. Using Eqns. (7) and (8):

$$EU_V(r) = \frac{0.99}{2}(1 + r)\,U(1) + \frac{0.01}{2}(1 + r)\,U(0.1)$$
$$EU_{V'}(r) = r\,U(1)$$

Represented graphically in Fig. 2.

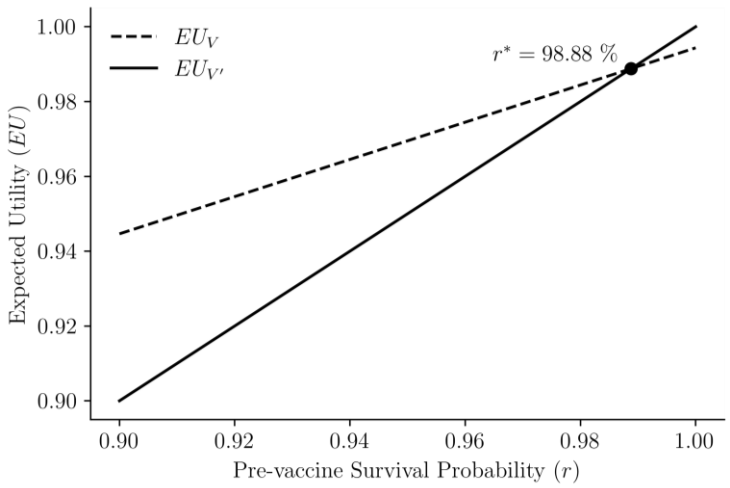

Figure 2: Expected utility for vaccinating (EU_V) and not vaccinating ($EU_{V'}$) against the pre-vaccine survival probability (r)

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Example 3. An agent's probability of developing narcolepsy after taking a vaccine is set at $q = 4.333 \times 10^{-5}$, and his life quality with narcolepsy is 25 % ($\Lambda_S = 0.25$). The effectiveness of the vaccine at preventing his death from the targeted disease is 90 % ($\varepsilon = 0.9$). The agent follows a quarter-circle utility function. Will the agent choose to get vaccinated?

Ans. By Eqn. (11),

$r^* \approx 99.99837$ %

This q value mainly concerns children and adolescents, as they were the ones at risk for narcolepsy during H1N1. So, it is appropriate that all people (with or without underlying conditions) in the 0–19 age range in the UK (Table 3) would choose to *not* get vaccinated. If this example is applied to all age ranges, then according to the Stockholm data (Table 2), all men and women without underlying conditions below the 40–49 age range would also choose to *not* get vaccinated.

Example 4. The probability that an agent survives an infection from a certain disease is 99.99995 % ($r = 0.9999995$). If he takes a vaccine against this disease, he has some chance of developing a side effect. For any side effect, his life quality is 95 % ($\Lambda_S = 0.95$). The effectiveness of the vaccine at preventing his death from the targeted disease is 100 % ($\varepsilon = 1$). The agent follows a quarter-circle utility function. At what probability of side effects is he indifferent between taking and not taking the vaccine?

Ans. By Eqn. (12),

$q^* \approx 0.04$ %

If $q < q^*$ then the agent will decide to get vaccinated. This is shown graphically in Fig. 3.

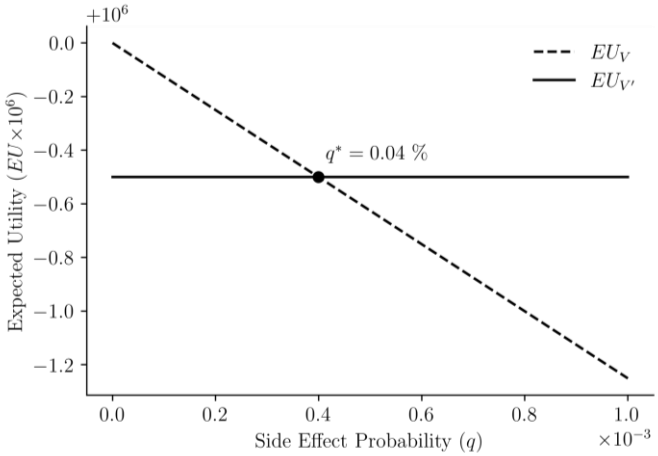

Figure 3: Expected utility of vaccinating (EU_V) and not vaccinating ($EU_{V'}$) against the probability of side effects (q)

4. MODEL EXTENSIONS

Irrespective of what is in the individual's best interests (maximizing expected utility), coercion and mandates can force him to get vaccinated. Such mandates are ethically dubious considering that SARS-CoV-2 is so infectious, and that the vaccines are non-sterilizing — meaning mandates are likely to accomplish little.

It is worthwhile then to try and study the reasons why people get vaccinated, given that they have just been presented with the latest relevant statistics. The author conjectures that most people simply overestimate the probability of death from COVID-19, and are ill-informed of the possible vaccine side effects. This would mean that those few who refuse to get vaccinated, irrespective of the coercion, are simply more knowledgeable. In this case the developed model does not need to be updated.

Although, there is still the possibility of people having the current knowledge, but get vaccinated due to the coercion. This would imply that the mandates reduce the life quality while unvaccinated, but that there would likely be a 'cutoff' that divides the regions where the mandates do and do not influence the decision. So, an agent that is knowledgeable would stay unvaccinated if there were only small restrictions placed on him. If, however, it becomes illegal to be unvaccinated (for example), then the threshold is reached and he decides to get vaccinated. As a proposal, there could simply be some constant k that reduces the life quality by a percentage. Then, once an indifference point k^* is crossed, he gets vaccinated.

4.1 Coercion Modeling

Deriving from Eqn. (9), but using $k\Lambda$ as the life quality in $EU_{V'}$:

$$\begin{aligned} p\,(1-q)\,U(\Lambda) + p\,q\,U(\Lambda_S) &= \frac{p-\varepsilon}{1-\varepsilon}\,U(k\Lambda) \\ \frac{1-\varepsilon}{p-\varepsilon}\,[\,p(1-q)\,U(\Lambda) + p\,q\,U(\Lambda_S)\,] &= U(k\Lambda) \end{aligned} \tag{13}$$

Where k is the degree of coercion inflicted on the agent, $k \in [0,1]$.

Remark 2. When $k = 1$ there is no coercion, and when $k = 0.5$ the coercion halves the agent's life quality.

To simplify notation:

$$\text{let } j = \frac{p\,(1-\varepsilon)}{p-\varepsilon}\,[\,(1-q)\,U(\Lambda) + q\,U(\Lambda_S)\,] \tag{14}$$

Assuming *U* is the quarter circle utility function — Eqn. (1) — then using Eqn. (13) and Expr. (14):

$$\begin{aligned} j &= \sqrt{1-(k\Lambda-1)^2} \\ j^2 &= 1-(k\Lambda-1)^2 \\ 0 &= k^2\Lambda^2 - 2k\Lambda + j^2 \end{aligned} \tag{15}$$

Then k is solved for using the quadratic equation:

$$\begin{aligned} k &= \frac{2\Lambda \pm \sqrt{4\Lambda^2 - 4\Lambda^2 j^2}}{2\Lambda^2} \\ &= \frac{2\Lambda \pm 2\Lambda\sqrt{1-j^2}}{2\Lambda^2} \\ &= \frac{1 \pm \sqrt{1-j^2}}{\Lambda}, \end{aligned}$$

which is of the form

$$k = \frac{1+x}{\Lambda},$$

but since $\Lambda \leq 1$, Λ is non-negative, and $1 - j^2 > 0$, then $x < 0$ so that $k \leq 1$ remains true.

$$\therefore k^* = \frac{1-\sqrt{1-j^2}}{\Lambda} \tag{16}$$

Where k^* is the level of coercion at the point at which the agent is indifferent between getting and not getting vaccinated.

4.2 Coercion Examples

The following examples show that very little coercion is actually needed to force an agent to change his decision. This likely illuminates why mandates and coercion are so ubiquitous and successful all over the world.

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Example 5. An agent must decide if he will get vaccinated, where: $\Lambda = 1$, $\Lambda_S = 0.5$, $\varepsilon = 0.75$, $q = 1$ % and $r = 99.99$ %. At what level of coercion will the agent be indifferent in his choice?

Ans. By Eqn. (16):

$$k^* \approx 94.97\ \%$$

Which means the agent's life quality must be reduced by only about 5 % for the coercion to be successful.

Note. Fig. 4 is a graphical representation of how k^* changes with a change in q (while all other variables stay the same as in Example 5). In the negative region of the q_1 curve, the agent will decide to *not* get vaccinated, as the coercion is not strong enough. If his side effect probability were to reduce to q_2, then the curve shifts outwards, which increases the coercion cutoff by about 4 %. This makes him less able to resist coercion.

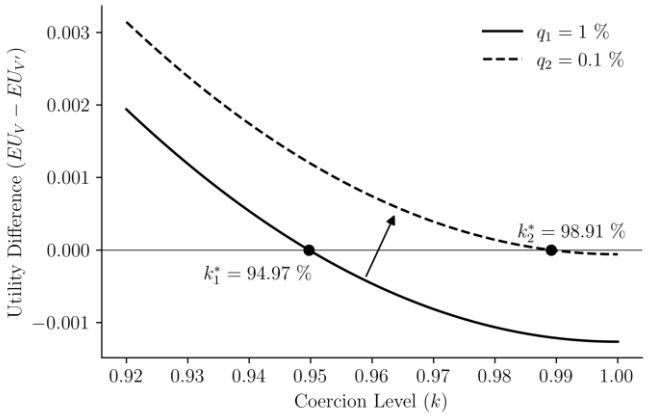

Figure 4: Utility difference against k, for two different side effect probabilities

Example 6. Continuing from Example 3 concerning narcolepsy: $q = 4.333 \times 10^{-5}$, $\Lambda_S = 0.25$, $\Lambda = 1$, $\varepsilon = 0.9$. The agent is a 10-year-old girl with $r = 99.99996$ %. Coercion is at a 99.5 % level. Will she get vaccinated?

Ans. Using Eqn. (16),

$k^* \approx 99.46$ %

but

$$k^* < k = 99.5\ \%$$

Therefore, she will *not* get vaccinated.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

A framework was developed to model the decision to take or not to take a vaccine, while using the maximization of expected utility as the underlying structure. This model was needed to understand and predict if an individual would get vaccinated against COVID-19 without any form of external coercion. The model breaks away from the typical monetary-based behavioral modelling so as to incorporate death (utility of zero), and to not rely on spatial and temporal variables influencing the cost of medical care. A quarter circle utility function was proven to be appropriate — given the proposed properties of a function that can model health decisions. Available statistics of COVID-19 deaths and vaccine side effect probabilities were used in the model. By relating the expected utility of getting vaccinated against the expected utility of *not* vaccinating, it was shown that the model aligned well with the risks incurred on specific cohorts (such as myocarditis mainly affecting young men and boys). In effect, the model proves a logical decision-making process to refuse a vaccine:

if there is a significant chance of severe side effects, and if there is already a low probability of death from the disease the vaccine is supposed to protect against. However, an extension to this model that incorporates external coercion shows that little of it is needed to force an agent to get vaccinated. This observation shows why mandates are so commonplace all over the world, and are so successful in driving up vaccination numbers.

5.2 Recommendations

- Modelling was kept simplistic so as to be tractable, but this meant that only one vaccine side effect could be compared to the probability of death from the disease the vaccine protects against. Including multiple side effects, both from the vaccine and from the disease, could be combined in a more generalized model.
- It is theoretically possible to calculate the life quality with side effects (Λ_S) if the other variables are known; instead of needing to estimate it based on reasoning. It is thus recommended to further explore the estimation of Λ_S.
- More work must be done to include the effects of external coercion on health decisions, as it is likely to be the most influential factor on an individual's decision to get vaccinated.

APPENDIX - A. RAW COVID-19 STATISTICS

Statistics on deaths and cases by age range. Not all age ranges produced by official sources were the same (groups of 5 years instead of 10), so some inference had to be made from other statistics (like case proportions).

Table A1: UK COVID-19 statistics from official sources, including FOI requests [8, 9]

Age	Mortality rate (per 100,000 cases)	Total number of deaths	Number of deaths *not* involving comorbidities
0–19	0.9	36[2]	7[1]
20–29	2.1	89	19[1]
30–39	7.4	331	73[1]
40–49	22.8	962	91[1]
50–59	65.9	2955	350
60–69	192.9	6746	523
70–79	553.9	15473	926
80+	2376.4	39897	2485

[1] Data for these age ranges are clumped together in a 0–44 age range in the original FOI request. These death numbers were estimated from the UK's proportion of total deaths for younger age groups.
[2] The original data simply gives '<10' as the number of deaths for the 0–5 and 5–9 age ranges, so the maximum of 9 was taken for each.

Table A2: Raw Canadian COVID-19 statistics as of August 8 2021 [10–12]

Age	Number of deaths	Proportion of total cases (%)
0–19	15	19.3
20–29	66	19.3
30–39	149	16.4
40–49	344	14.6
50–59	1007	12.9
60–69	2583	8.0
70–79	5407	4.2
80+	17061	4.9

Total cases: 1,438,743
Total deaths: 26,632

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Table A3: Raw German COVID-19 statistics as of September 7 2021 [13, 14]

Age	Number of cases	Age	Number of deaths
0–4	106832	0–9	15
5–14	319338	10–19	11
15–34	1210420	20–29	88
35–59	1499689	30–39	248
60–79	557263	40–49	736
80+	292073	50–59	3182
		60–69	8468
		70–79	19127
		80–89	40832
		90+	19353

Total cases: 3,985,615
Total deaths: 92,060

Table A4: Raw Japanese COVID-19 statistics as of August 25 2021 [15]

Age[1]	Number of cases	Number of deaths
0–9	57575	0
10–19	123075	0
20–29	331279	13
30–39	213886	41
40–49	202171	133
50–59	166804	355
60–69	87660	1037
70–79	67749	3144
80+	64808	8524

Total cases: 1,315,007
Total deaths: 13,247

[1] Some ages were recorded as 'undisclosed', so were not considered. In total there were 12,463 cases (0.94 %) and 338 deaths (2.49 %) from people with an unknown age. These percentage contributions were considered negligible.

Table A5: Raw USA COVID-19 statistics as of September 24 2021 [16, 17]

Age	Number of cases	Age	Number of deaths
0–4	802143	0–17	464
5–11	1649666	18–29	3376
12–15	1375824	30–39	9755
16–17	899898	40–49	24642
18–29	7405917	50–64	114320
30–39	5526601	65–74	150792
40–49	4861416	75–84	179399
50–64	6469556	85+	189273
65–74	2381113		
75–84	1210641		
85+	668562		

Total cases: 33,251,337
Total deaths: 672,021

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Table A6: Raw Italian COVID-19 statistics as of September 14 2021 [18–21]

Age	Proportion of all cases (%)	Proportion of all deaths (%)
0–19	16.1	0.1
20–29	12.5	0.1
30–39	12.6	0.2
40–49	15.9	0.9
50–59	16.9	3.6
60–69	10.7	10.4
70–79	7.7	25.2
80+	7.7	59.5

Total cases: 4,649,906
Total deaths: 130,421

APPENDIX B. PROOFS

Proposition 1. *The quarter-circle utility function conforms to all properties laid out in Table 1, Section 2.1, and so is able to model health decisions.*

Proof. Properties 1 and 2 are trivial as

$$\begin{aligned} y(0) &= \sqrt{1-(0-1)^2} \\ &= \sqrt{1-1} = 0 \end{aligned}$$

and

$$\begin{aligned} y(1) &= \sqrt{1-(1-1)^2} \\ &= \sqrt{1-0} = 1\,. \end{aligned}$$

For Property 3,

$$\begin{aligned} \lim_{x\to 1^-} \frac{d}{dx}\sqrt{1-(x-1)^2} &= \lim_{x\to 1^-} \frac{1-x}{\sqrt{2x-x^2}} \\ &= \lim_{x\to 1^-}(1-x)\cdot \lim_{x\to 1^-}(2x-x^2)^{-\frac{1}{2}} \\ &= 0\cdot 1 \;=\; 0\,. \end{aligned}$$

And for Property 4,

$$\begin{aligned} \lim_{x\to 0^+} \frac{1-x}{\sqrt{2x-x^2}} &= \lim_{x\to 0^+}(1-x)\cdot \lim_{x\to 0^+}(2x-x^2)^{-\frac{1}{2}} \\ &= 1\cdot \lim_{x\to 0^+} e^{\ln(2x-x^2)^{-\frac{1}{2}}}, \end{aligned}$$

by the constant-base power rule

$$= e^{\left(\frac{1}{2}\lim\limits_{x\to 0^+}\ln\frac{1}{2x-x^2}\right)},$$

which diverges to $+\infty$ because e^z is non-decreasing and $\lim_{x\to 0^+}\ln\frac{1}{2x-x^2}$ diverges to $+\infty$. Hence, the quarter-circle utility function conforms to all properties and so is able to model health decisions.

Conjecture 2. *The n^{th} root utility function is able to model health decisions, according to the properties laid out in Table 1, Section 2.1.*

Disproof. Concerning Property 3,

$$\lim_{x\to 1^-} \frac{d}{dx}\left(x^{1/n}\right) = \lim_{x\to 1^-} \frac{1}{n} x^{\left(\frac{1}{n}-1\right)}, n > 1$$
$$= \frac{1}{n} \neq 0 .$$

Hence, the n^{th} root utility function fails to conform to all properties required to model health decisions.

APPENDIX C. ERRONEOUS MYOCARDITIS INCIDENCE RATE REPORTING

A paper by Singer et al. concluded that heart inflammation "from primary COVID19 [sic] infection occurred at a rate as high as 450 per million in young males," and that this rate is 6 times higher than that of taking a COVID-19 vaccine in the same cohort [44].

Firstly, Singer et al. used a large healthcare provider (hospital) database to determine the number of positive COVID-19 cases in each cohort. But, these populations were the number of persons that made use of the respective hospitals' services, for services related to COVID-19 (testing and admissions due to illness). The 12–17 cohort only contained 6,846 people, so Singer et al. tried to match this figure to the number of infections they should be seeing (as most young people are not hospitalized with COVID-19, and hospitals are not the only places to get tested). However, they estimated the hospital admission, treatment or diagnosis rate at ~27 % for the 12–17 cohort. This completely ignores the millions of PCR-confirmed COVID-19 infections, and that young people are especially prone to being asymptomatic [45]. A more accurate rate would be closer to 2 % [46, 47]. Singer et al. then arbitrarily decided to double the myocarditis cases recorded to 12 to try and include those that may have sought treatment elsewhere. Using more reasonable estimates gives a rate of 18–35 per million for myocarditis from COVID-19 infection, much less than the multiple hundreds per million concluded [44], and still lower than the rates of vaccine-induced myocarditis discussed previously (Section 2.3.2). This value is likely still inflated as more recent research gives the rate at 7 per million [24].

Secondly, if COVID-19 really did cause so much myocarditis, then this fact would have been very prominent before the COVID-19 vaccines attained emergency-use approval. In fact, myocarditis cases per month increased by 62 % after vaccines were brought to the public, compared to the entirety of the pre-vaccine period (2020), and long before the spike in omicron-variant cases (December 2021) [48].

Therefore, the paper by Singer et al. must be rejected as it has multiple statistical issues, in addition to the inability to correlate with more recent research concerning myocarditis as a result of COVID-19 infection.

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