Editors' Note:

The following article on a topic of considerable individual and public health significance presents disturbing information and leads to conclusions of a controversial nature. Letters to the Editors with comments and discussion on this important topic are welcome.

A Critical Review of the Physics and Statistics of Condoms and their Role in Individual versus Societal Survival of the AIDS Epidemic

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Condom failure rates for HIV are substantially greater than for pregnancy, even for highly motivated people who may reach the limit set by allowed manufacturing imperfections. This makes condoms ineffective for lifelong protection from HIV-infected sexual partners; therefore, in general, condoms provide inadequate risk reduction for the individual. Nevertheless, they are sufficiently effective that if everyone used condoms, the AIDS epidemic would stop. Quantitative public health goals to reduce the "reproductive rate" of HIV from an estimated 4–12 people infected per infected person to below 1 are needed. Government and scientific testing of condoms could be improved statistically and by utilizing relevant physics.

The chance of HIV transmission depends on whether one's partner is actually infected and the infectivity of the virus, which in turn depends on virulence, concentration, duration of contact, cofactors, etc. Defining "exposure" to mean direct genital or anal contact with infected semen or vaginal fluids, I will examine the degree of control afforded to the individual and society by condoms when they are used to prevent exposure

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to HIV. Since infectivity determines whether a single exposure is of high or low risk, I also review its estimates.

The confidence that people can have in public health messages on using condoms for avoiding AIDS is diminished because they are given in qualitative terms: "To reduce your risk, always use a condom during a sexual encounter,"[1] or, "Condoms may not provide total protection, but they will help considerably if used properly and always";[2] "But condoms are far from being foolproof."[3] Occasional references to "90% effectiveness" are widely accepted.[4] The public distribution of condoms,[5] the promise of support for AIDS research for each condom sold,[6] and the quadrupled value of shares in condom companies[7] would seem to convey a high degree of confidence in their effectiveness. I will examine quantitatively[8] the odds of condom failure when they are used during a lifetime of sexual activity, and critically review the statistical and physical bases for the confidence that has been placed in condoms as a means of avoiding HIV and AIDS. While E. Koop[9] has noted "a near-complete lack of research on condom failure rates and causes," there is enough evidence available now to put the use of condoms in quantitative perspective.

PUBLIC HEALTH TARGETS

The extent of behavioral change needed to stop the AIDS epidemic may be considerable: "R_0, . . . the basic reproductive rate of the infection, defined in biological terms as the average number of secondary infections produced [new individuals infected] when an infected individual is introduced into a wholly susceptible population, . . . has a value [for AIDS] of at least 5, and possibly more. In view of the biological interpretation of R_0, this is a disturbing finding. The infection can establish itself endemically so long as R_0 remains above unity; alternatively, eradication requires changes in sexual habits . . . to bring R_0 below unity. The larger the original value of R_0, the more difficult is the task of bringing about changes of magnitudes sufficient to drive R_0 below unity and thus eventually to eradicate the infection."[10] The value of R_0 is now estimated[11] at 4–12. If public health agencies would establish, monitor and attain a quantitative target of reducing R_0 below 1, the epidemic would stop. In the section, Choices for Government, I will consider the possibility that widespread condom use could lead to $R_0 < 1$.

THE EFFICACY OF CONDOMS FOR AVOIDING PREGNANCY

Miller[12] gives the following figures for the typical effectiveness, ε, of birth control methods "based on use by couples for one year": condom (good brand) plus spermicide, 95%; condom alone (good brand), 90%; condom alone (cheap brand), 70% (see also [13–27]). Why aren't these methods 100% effective? Condoms are known to break,[28,29] to age[30–32] or be damaged in their packages, fall off,[33] get pulled off, etc. Sometimes we just don't pay enough attention, put them on or take them off improperly, can't read the directions,[34] or even fall asleep on the job! The effects of alcohol, marijuana, prescription and over the counter drugs, illegal drugs, or even just exhaustion, all often coincide with intercourse. Kaplan[35] suggests that "secretions . . . can get around and over a condom even if it does not break" (see also [36]). As I will show below, the allowed rate of manufacturing defects may be one of the most important factors. J. J. Crawford (University of North Carolina) put red dye in the mouth of a dummy to show how possibly infected saliva is distributed around a dentist's office. Perhaps an analogous experiment should be done with condoms.

To understand the degree of protection afforded by condoms, let us take the most optimistic case, $\varepsilon = 95\%$. A 95% annual effectiveness means a 5% chance of pregnancy each year, or 1 in 20 chance per year. To calculate one's chance of getting through 2 years of "safe sex" without a pregnancy, we have to multiply these figures together: $0.95 \times 0.95 = 0.9025$. Thus in 2 years of "safe sex" with good condoms and a spermicide we have about an 0.10 chance of pregnancy, or 10%. The odds are now up to 1 in 10. Use of condoms without a spermicide reduces the effectiveness per year to 90%, which compounds even more rapidly (Table 1). The general formula for probability of pregnancy is $1\text{-}\varepsilon^y$, where ε is the effectiveness per year and y is the number of years. Of course, in life declining fertility also intervenes to reduce pregnancy rates. Nevertheless, the unplanned pregnancy with the use of condoms is a common event.

Much has been said about training people in the correct use of condoms.[37] However, even amongst those who have the lowest known failure

TABLE 1
Probability of Exposure

		Effectiveness/year						
Time (years)	ε:	97.%	95.%	90.%	80.%	70.%	57.%	25.%
1		3.%	5.%	10.%	20.%	30.%	43.%	75.%
2		6.%	10.%	19.%	36.%	51.%	68.%	93.8%
3		9.%	14.%	27.%	49.%	66.%	81.%	98.4%
4		11.%	19.%	34.%	59.%	76.%	89.%	99.6%
5		14.%	23.%	41.%	67.%	83.%	94.%	99.9%
10		26.%	40.%	65.%	89.%	97.2%	99.6%	•
20		46.%	64.%	88.%	98.8%	99.9%	•	•
30		60.%	79.%	96.%	99.9%	•	•	•
40		70.%	87.%	98.5%	•	•	•	•
50		78.%	92.%	99.5%	•	•	•	•

The probability of first exposure, given an annual effectiveness ε for avoiding exposure, versus number of years of potential exposure. • indicate > 99.9%.