

Resistance Is Futile ... or Is It?

The Immunity System and HIV Infection

by

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Part I – HIV and the Immune System

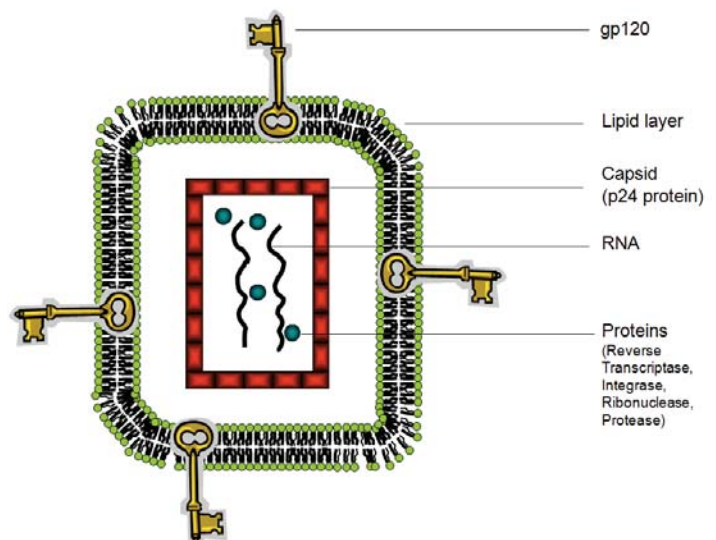
The vast majority of people are susceptible to HIV infection. However, in the 1990s, several individuals noticed that despite repeated exposure to the HIV virus they remained HIV negative. This could be due to the fact that these individuals were extremely lucky, or perhaps there was something different about them that made HIV infection less likely.

William Paxton and his colleagues at the Aaron Diamond AIDS Research Center in New York became interested in this phenomenon of HIV protection. In this case study, you will retrace the steps and experiments that these researchers performed to understand the mechanism underlying the protection against HIV (Paxton et al., 1996).

To this end, you must first review a few facts about the HIV virus, the immune system, and HIV infection.

The HIV Virus

The virus particle is spherical in shape. Its structure consists of multiple enclosed layers, like the skin of an onion. It is considerably smaller than human cells. At the center of a virus particle are two copies of its genetic material. HIV encodes its 9 genes using the nucleic acid molecule RNA (by comparison, our cells use DNA for this capacity). At the core of the virus particle are also proteins important for the replication of the virus (reverse transcriptase, integrase, protease, ribonuclease). The RNAs and proteins are wrapped in a protein coat (called the capsid) made of the protein p24. The capsid in turn is wrapped in a double layer of phospholipids. Finally, there are proteins that stick out of the lipid layer, such as gp120 (sometimes called Env).

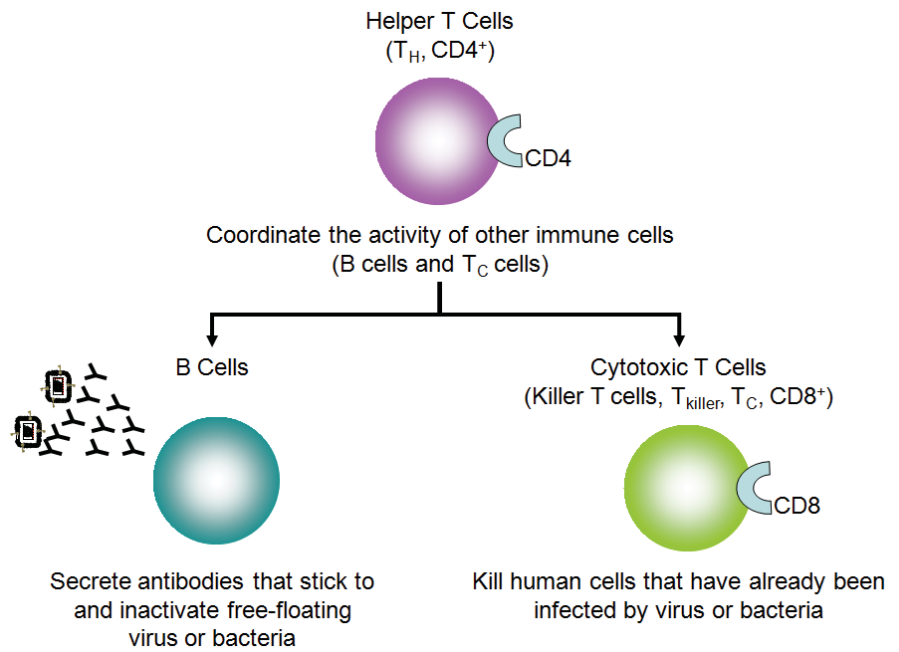


This latter protein gives HIV its specificity: gp120 interacts with specific proteins found only on certain human cells (like a lock and key mechanism), allowing the HIV virus to infect specific cell types.

The Immune System

The immune system is a very complex system. Here, we review only those aspects that are relevant to this case.

B cells (sometimes called B lymphocytes, plasma cells, plasma B cells, plasmocytes, or effector B cells) are white blood cells involved in neutralizing a virus or bacteria that have not yet infected a cell and are “free floating” in the body (this is called the humoral immune response). B cells secrete a protein called an antibody into the circulatory system. Each antibody binds to a particular virus or bacteria very specifically and strongly. When antibodies bind to a virus or to bacteria, the foreign object is inactivated. Therefore, when B cells secrete antibodies, they “take out” free-floating foreign invaders.



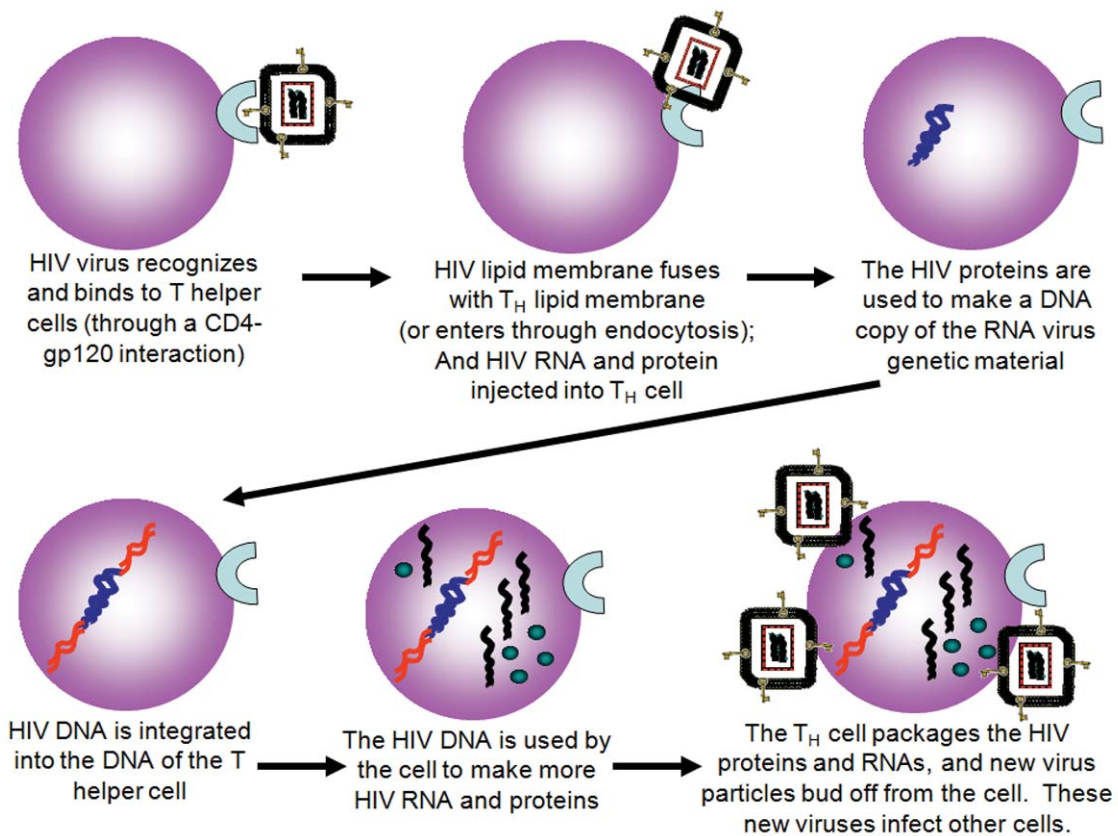
Cytotoxic T cells (sometimes called killer T cells, or T_C or T_{killer} or cytotoxic T lymphocytes [CTL] or CD8⁺) recognize human cells that have already been infected by a foreign virus or bacteria (this is called the cellular immune response). Their job is to kill these infected cells. So while B cells remove free floating virus particles, T_C cells remove virus particles that have already made their way inside human cells by killing the infected cells. On their cell surface is a protein called CD8, which is why they are sometimes called CD8⁺ cells.

T Helper cells (sometimes called T_H, or CD4⁺ cells) do not directly interact with foreign bodies. They are the “organizing centers” of the immune system, coordinating the action of cytotoxic T cells and B cells. Without them, T_C and B cells do not work effectively. On their cell surface is the protein CD4, which is why these cells are sometimes called CD4⁺ cells.

HIV Infection

HIV targets and infects T_H cells. On the surface of the HIV particle is the protein gp120. This protein recognizes and binds (with a lock and key specificity) the CD4 protein on the surface of T helper cells. Once a virus particle has docked, its lipid membrane either fuses with the human cell’s membrane, or the virus is brought in by endocytosis, and the contents of the virus are released inside the cell.

Recall that the HIV virus has an RNA genome. If the virus is to hijack the cell machinery, its genetic information must first be converted into the genetic information used by the cell (i.e., DNA). This is the job of the protein reverse transcriptase, which the virus brought into the cell. Reverse transcriptase makes DNA copies of the RNA virus. This newly made DNA is then integrated into the genome of the human cell. The human cell then uses the 9 genes as it would its own. It therefore produces all the proteins and RNA needed to make more virus particles. The newly-made virus particles bud off of the T helper cell, which is now a virus-producing factory.



Let's review this information and think of its implication for the study of individuals with an apparent resistance to HIV infection.

Questions

1. HIV is a retrovirus (a virus that uses reverse transcriptase).
 - a. What is reverse transcriptase?
 - b. How is a retrovirus different from other viruses?
 - c. How does a retrovirus infect a cell and reproduce itself?
2. Review of the immune system.
 - a. What is a T cell?
 - b. What varieties of T cell exist? How are they functionally different?
 - c. What are their roles in the human body?
 - d. How is each T cell variety differentiated from the others (molecularly)?
3. Immune system and HIV
 - a. Which type(s) of immune cells is/are targeted by HIV?
 - b. Why are other cells not targeted by the virus?
 - c. How should cytotoxic T cells respond to the initial phase of HIV infection (when some T helper cells are still functioning)? Explain your reasoning.

- d. As time progresses, why do the cytotoxic T cells stop responding to the HIV infection? Propose an explanation.
 - e. What happens to the immune system after HIV infection? Why? Can this account for the symptoms of AIDS (i.e., immunodeficiency, or the inability to defend against any foreign invaders like viruses and bacteria)?
 - f. Why do you suppose that there is a delay between the time of HIV infection and the appearance of symptoms (and AIDS)?
 - g. How does HIV evade the immune system?
4. HIV protection
- a. Consider how HIV infects cells and reproduces. Also consider how the immune system fights off HIV infection. Humans differ by having mutations that result in slightly different proteins and immune function. Suggest as many hypotheses as possible to explain why some individuals might be protected against HIV infection. In other words, where and how might new viral infections be stopped? What could be different about the people who seem protected against HIV that caused viral replication to stop? Come up with at least three possibilities.

Part II – Paxton’s Hypotheses about HIV-Protected Individuals

Paxton and his colleagues had a few hypotheses about why some of the individuals exposed to HIV were protected against this virus.

CD8⁺ lymphocyte inhibition of HIV-1 replication (“Super Cytotoxic T Cells” Hypothesis)

Perhaps the reason that some individuals were protected against HIV is because they had cytotoxic T cells that were better and faster at recognizing infected T helper cells. This ability allowed the immune system to rid the body of any HIV infection before the virus could replicate inside T helper cells and transform these cells into HIV factories.

CD4⁺ infectibility and efficiency of viral replication (“Super T Helper Cells” Hypothesis)

Perhaps the T helper cells of the protected individuals were different, preventing the infection and replication of the virus inside the cell. There are many steps necessary for viral infection and replication inside T helper cells and any of them could be impeded.

Questions

1. Classify each of *your* proposed hypotheses into the two categories proposed by Paxton and his colleagues (*Note*: some hypotheses may fit into neither category).
2. How might you test each of your hypotheses? Propose an experiment. What are your controls? Experimental conditions?

Part III – Predictions from Paxton’s Two Hypotheses

Paxton and his colleagues recruited 25 volunteers who claimed to have had repeated exposure to the HIV virus and yet were not infected with HIV. He also enlisted the help of nine individuals not exposed to the HIV virus (and who tested negative for the virus). This latter group is the control, whose response to HIV should be the same as the response of the majority of people.

Paxton and his colleagues wanted to identify which of their two hypotheses might be correct. The problem with working *in vivo* is that it is unethical to expose individuals to HIV. In addition, the human immune system is complex, with multiple interactions. To isolate the action of T helper cells, cytotoxic T cells, and the HIV virus, Paxton and his colleagues worked in test tubes.

Paxton isolated T helper cells and cytotoxic T cells from individuals in each group. He then performed the following experiments:

- In one tube, he mixed HIV virus and T helper cells.
- In another tube, he mixed HIV virus, T helper cells, and cytotoxic T cells.

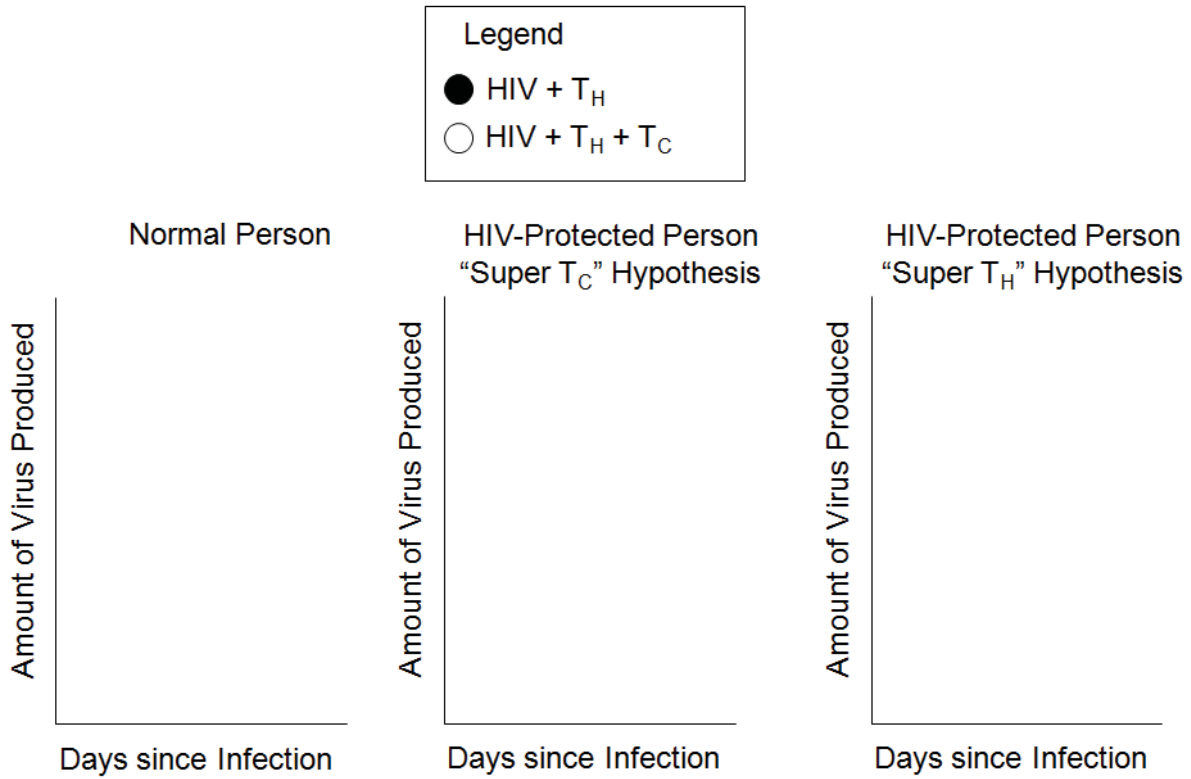
He monitored the accumulation of virus in the test tube over time by measuring the amount of p24 proteins produced.

Questions

1. Design of the experiment:
 - a. Why were HIV and T helper cells mixed in the presence and absence of cytotoxic T cells?
2. For control individuals:
 - a. If you mix HIV and T helper cells in a test tube, what would you expect to happen? Why?
 - b. If you mix HIV, T helper cells, and cytotoxic T cells in a test tube, describe what you would expect to happen and why it occurs that way.
3. For protected individuals:
 - a. Assuming that the “Super Cytotoxic T Cells” Hypothesis is correct, then when you perform the experiment using T helper cells and cytotoxic T cells from protected individuals:
 - i. If you mix HIV and T helper cells in a test tube, what would you expect would happen? Why?
 - ii. If you mix HIV, T helper cells, and cytotoxic T cells in a test tube, describe what you would expect to happen and explain your reasoning.
 - b. Assuming that the “Super T Helper Cells” Hypothesis is correct, then when you perform the experiment using T helper cells and cytotoxic T cells from protected individuals:
 - i. If you mix HIV and T helper cells in a test tube, what would you expect to happen? Why?
 - ii. If you mix HIV, T helper cells, and cytotoxic T cells in a test tube, describe what you would expect to happen and explain your reasoning.
4. How is this experiment able to differentiate whether the mechanism of protection against HIV is through “Super T Helper Cells” or “Super Cytotoxic T Cells”?

5. Use the graphic provided below to illustrate the results you would expect to obtain for:
 - a. a normal/control person
 - b. a protected individual, assuming that the “Super Cytotoxic T Cells” Hypothesis is correct
 - c. a protected individual, assuming that the “Super T Helper Cells” Hypothesis is correct

Please note that each graph requires two lines (the two test tubes).



Part IV – Paxton’s Results

Below are Paxton’s results (from Figure 1 of his paper). The graphs produced in the top part come from control individuals (each graph represents the results of experiments performed using cells from one person) (Note: LP = Leukopac Preparation, or blood obtained from random blood donors; LW = Laboratory Workers, i.e., people working in the lab). The bottom graphics show 10 selected results from people claiming to be protected against HIV infection (Note: EU = Exposed Uninfected individuals).

The filled circles (●) represent the results of experiments in which HIV was incubated with T helper cells, and the empty circles (○) represent experiments where HIV + T helper cells + cytotoxic T cells were mixed in the test tube.

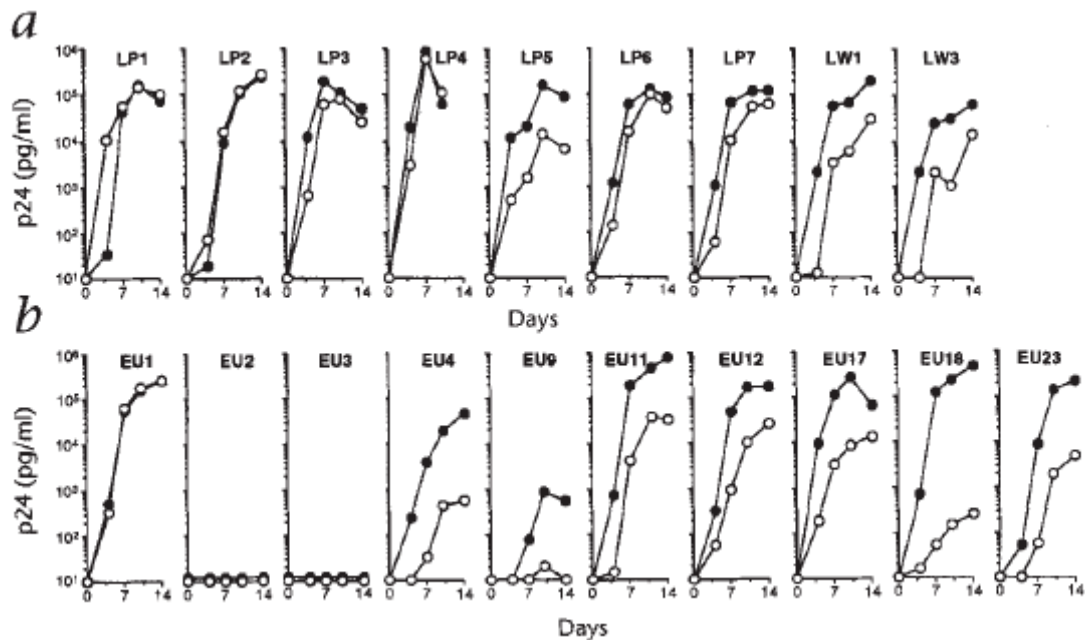


Figure 1 from: Paxton *et al.* (1996). Reprinted with permission of Macmillan Publishers Ltd: *Nature Medicine*, copyright 1996.

Questions

1. Do cytotoxic T cells provide protection from HIV in control individuals?
2. Try to identify patterns in the results. Can the individual experiments performed using cells from protected individuals be grouped into categories? If so, how many? Classify each subject into the different categories.
3. Compare these results with what you had predicted in the previous section.
 - a. Are the results of the controls as you expected?
 - b. Which of Paxton’s hypotheses seem to be validated by the results of the protected individuals? Why?
 - c. What do you make of EU1? How do you account for his unusual response?

Part V – The “Super T Helper Cell” Mechanism

From the results of this experiment, it is apparent that EU₁ has either been lucky so far, or exhibits a mode of protection not anticipated by Paxton’s team. EU₂ and EU₃ do not appear to be infected by the HIV virus at all (“Super T Helper Cells”). The remaining protected individuals exhibit different degrees of infection with very active cytotoxic T cells to slow down the progression of new infections (“Super Cytotoxic T Cells”).

Paxton’s team was particularly interested in protected subjects EU₂ and EU₃ and in investigating the mechanism of action of their protection against HIV. To investigate this, they performed an experiment where they mixed purified T helper cells from control or protected individuals with different strains of HIV-1. The goal was to determine whether all HIV-1 strains could infect the T helper cells from protected individuals. HIV-1, the most common form of the virus and the one responsible for the pandemic, can be classified into two different types:

- M-tropic (also called non-syncytia-inducing (NSI) or R₅ HIV-1) strains, and
- T-tropic (also called syncytia-inducing (SI) or X₄ HIV-1) strains.

This turned out to be a very informative experiment. About the same time, two other papers were published that clarified some of the differences between these two strains of virus.

- M-tropic HIV-1 strains must bind to two cell surface proteins to enter and infect a cell (Dragic et al., 1996):
 - the *CD4 protein* and
 - the beta-chemokine receptor *CCR5*.
- Conversely, T-tropic HIV-1 strains use slightly different proteins to enter and infect a cell (Feng et al., 1996):
 - the *CD4 protein* as well as
 - the alpha-chemokine receptor *CXCR4* (at the time called fusin).

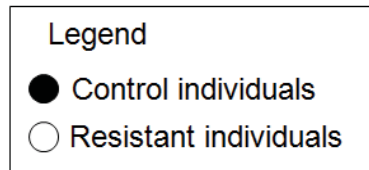
Armed with this information, we can look back at the experiment performed by Paxton’s team and investigate whether CD₄, CCR₅, CXCR₄, or another protein is mutated and “different” in individuals that are protected against HIV.

Here is the design of this experiment:

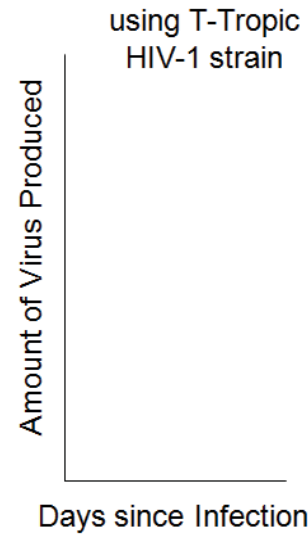
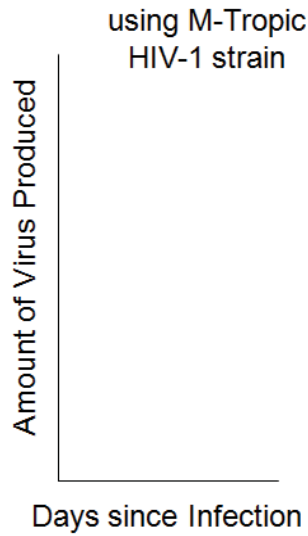
- In one tube: Mix HIV-1 (T-tropic strain) + T helper cells from a control person.
- In another tube: Mix HIV-1 (T-tropic strain) + T helper cells from a protected person.
- Monitor the appearance of p24 in the test tube (i.e., production of new virus) over time.
- In one tube: Mix HIV-1 (M-tropic strain) + T helper cells from a control person.
- In another tube: Mix HIV-1 (M-tropic strain) + T helper cells from a protected person.
- Monitor the appearance of p24 in the test tube (i.e., production of new virus) over time.

Questions

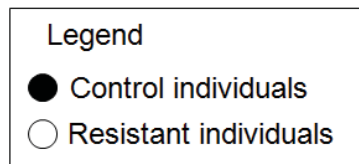
1. Let’s assume that protected individuals have an altered CD₄ protein (a mutation in the CD₄ gene) compared to controls that renders the protein unrecognizable by gp120. Use the graphs below to draw the results you expect to obtain from the above- mentioned experiment. Remember that each graph should have two lines, and review which proteins are required for infection by the two strains.



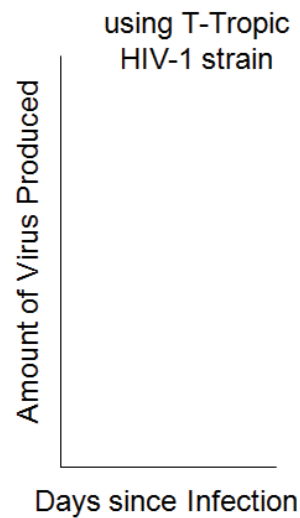
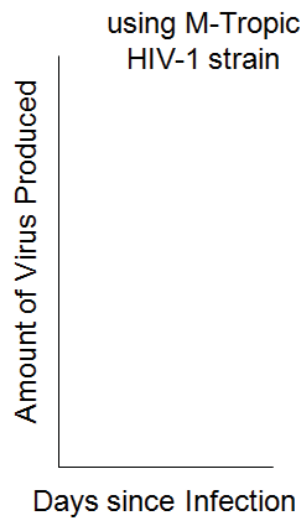
If controls and resistant individuals differ in their CD4 protein



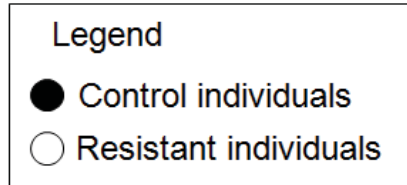
2. Let's assume that protected individuals have an altered CCR5 protein (a mutation in the CCR5 gene) compared to controls. Use the graphs below to draw the results you expect to obtain from the above-mentioned experiment. Remember that each graph should have two lines, and review which proteins are required for infection by the two strains.



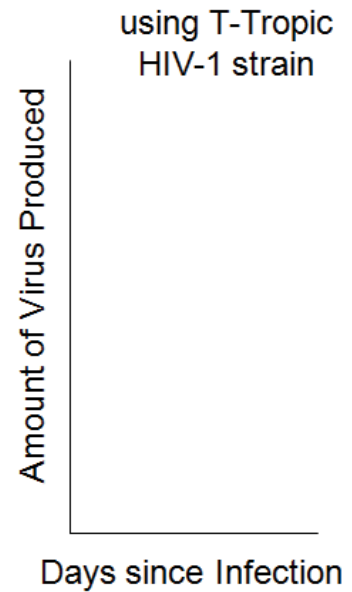
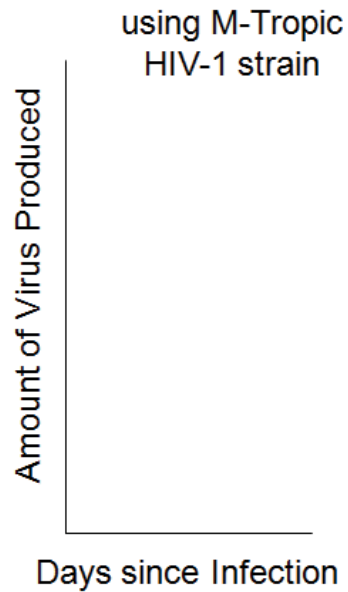
If controls and resistant individuals differ in their CCR5 protein



3. Let's assume that protected individuals have an altered CXCR4 protein (a mutation in the CXCR4 gene) compared to controls. Use the graphs below to draw the results you expect to obtain from the above-mentioned experiment. Remember that each graph should have two lines, and review which proteins are required for infection by the two strains.



If controls and resistant individuals differ in their CXCR4 protein



Part VI – Why Some People are Protected Against HIV

Here are Paxton's results from this experiment. The filled circles (●) represent results using T helper cells from controls, and empty circles (○) using T helper cells from protected individuals. The letters and numbers above each graph show the name of the HIV-1 strain used in the experiment.

M-Tropic strains:

- JR-CSF
- GT
- SF162
- AD-6
- 92US657

T-Tropic strains:

- NL4-3
- SF2
- SF162dbl
- SF162 R3H

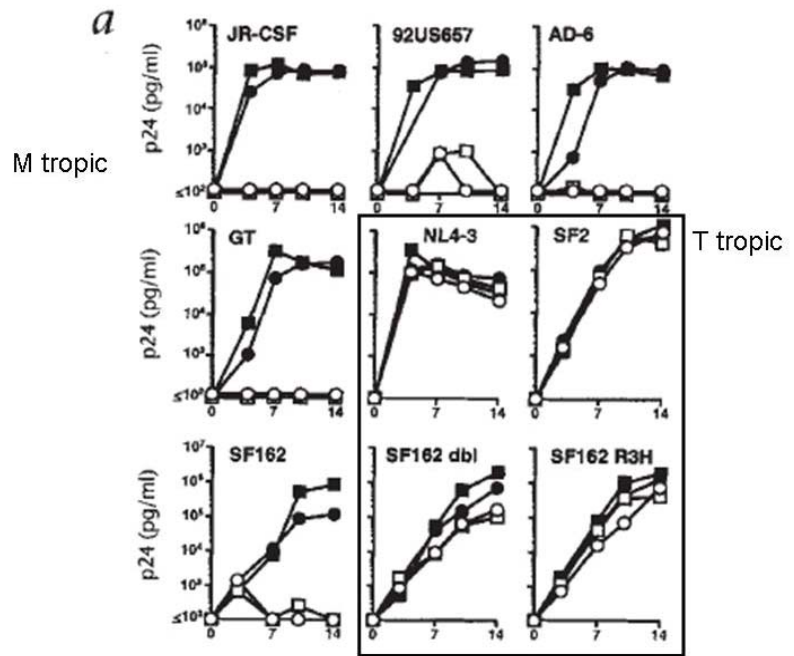


Figure 4 from: Paxton *et al.* (1996). Reprinted with permission of Macmillan Publishers Ltd: *Nature Medicine*, copyright 1996.

Questions

1. Infection:
 - a. Which strain(s) of HIV-1 can infect and replicate in the T_H cells of protected individuals?
 - b. Which co-receptor is used by this strain(s) of HIV-1 to infect these cells?
2. No infection:
 - a. Which strain(s) of HIV-1 can not infect and replicate in the T_H cells of protected individuals?
 - b. Which co-receptor is used by this strain(s) of HIV-1 to infect the cells?
3. Which of your theorized graphics do the results most resemble?
4. Based on this information, what is the mechanism of HIV protection in EU2 and EU3?
5. Are these people protected against all forms of HIV out there? What are the implications?

Part VII – Societal Implications of HIV Protection

Since this study, much has been learned about the mechanisms of protection against HIV. Here are some highlights.

“Super T Helper Cells”

In sexually transmitted HIV, the M-strain HIV-1 is the infectious agent 90% of the time (Ahmad, 2002). Thus, in most infections, the CD4 and CCR5 proteins are used by HIV to gain entry into T_H and infect the person.

Most of the individuals that are resistant through a “Super T Helper Cells” mechanism harbor the same mutation in their CCR5 gene. This is a deletion of 32 nucleotides that causes a frameshift in the reading sequence (Liu et al., 1996). Consequently, the cells of these individuals harbor no functional CCR5 protein. This does not appear to have any effect on the health of individuals. Since this mutation is found predominantly in populations of European decent, and since the mutation is first thought to have appeared in the population around 700 years, it has been hypothesized that the mutation confers resistance to *Yersinia pestis*, the infectious agent of the bubonic plague (Martinson et al., 1997). Others have suggested that the CCR5 mutation confers resistance to smallpox, and others still that this allele has spread in the population through neutral evolution (Sabeti et al., 2005). In populations of northern European descent, the frequency for CCR5 Δ 32 homozygous individuals is 1–3%, for heterozygotes it is about 14%, and for homozygote wild-type it is 83% (Sampson et al., 1996; Martinson et al., 1997).

Recent studies have shown that individuals homozygous for the CCR5 mutation are more prone to West Nile Virus infection (Glass et al., 2006). In addition, the lack of CCR5 protein makes mice more prone to hepatitis infection (Jefferys, 2006). These findings suggest that CCR5 might have a role in fighting other types of infections. This is an interesting finding, particularly in light of the fact that some experimental HIV therapies try to inhibit the expression of the CCR5 protein in healthy individuals.

As you probably have guessed from your answer to the questions in the previous section, some homozygous CCR5 Δ 32 individuals have tested positive for HIV infection (Biti et al., 1997; O’Brien et al., 1997).

Question

1. It is a relatively simple procedure to test the genotype of a person at the CCR5 gene to determine whether they have the CCR5 Δ 32 mutation. Should a person wishing to have their genotype tested be allowed to do so? What are the arguments for and against genotype testing of the CCR5 gene?

“Super Cytotoxic T Cells”

Looking back to Figure 1 of Paxton’s paper (Part IV of this case study), it seems that subjects EU4, 9, 11, 12, 17, 19, and 23 remained HIV negative despite repeated exposure to the virus by a mechanism that did not involve “Super T Helper Cells.” In fact, starting in the early 1990s, there were reports of an exposed child, health care workers, and Kenyan prostitutes, all of which sustained repeated exposure, but who remained uninfected (Rowland-Jones et al., 1993; Pinto et al., 1995; Rowland-Jones et al., 1998). While luck may have played a part, the studies revealed that such individuals had unusual HIV-specific cytotoxic T cell activity. In fact, in the case of the immune Nairobi sex workers, it seems that their T_C are more active, respond to different signals, and are involved in the production of more interferon molecules than normal (Kaul et al., 2000; Kaul et al., 2001a; Kebba et al., 2004; Alimonti et al., 2006). Interferons are proteins released by an infected cell to warn other cells of the infection. The warned cells then take defensive measures

to protect themselves against infection. Similar results were found in studies of intravenous drug populations and partners of HIV-infected individuals (Biasin et al., 2000; Makedonas et al., 2002; Lo et al., 2003; John et al., 2004). Interestingly, it seems that repeated exposure is required for this form of immunity and that it is reduced when uninfected individuals reduce the frequency of their risky behavior (Kaul et al., 2001b; Yang et al., 2002).

Question

2. This mechanism of protection against HIV seems to rely on continued exposure to maintain the immunity. However, the mechanisms causing the protection are not well understood and despite relative immunity these people could still be infected. What would you recommend to a person engaged in high risk activity that appears to exhibit protection against HIV-1? What leads you to make these recommendations?

“Super B Cells and Antibodies?”

The body’s first line of defense against HIV are the antibodies secreted in the mucosal surfaces (mouth, vagina, urethra). HIV-specific antibodies have been isolated in the mucus of resistant individuals engaged in oral, vaginal, or anal sex with HIV-infected individuals (Hirbod et al., 2008; Hasselrot et al., 2009). Control subjects did not produce this antibody response in their secretions. These antibodies appear to recognize and inactivate HIV virus in a test tube. Whether these antibodies help protect the uninfected individuals is an active area of study.

Questions

3. A recent article in a popular science magazine (Wallace, 2009) reported on the study that uninfected partners of HIV-infected men who practice oral sex have higher levels of HIV-specific antibodies in their saliva. The title and subtitle of the articles were: “HIV resistance through oral sex: A new study suggests that repeated exposure can help produce resistant antibodies.” Discuss the accuracy of this title. Does it represent what’s known about this field of investigation appropriately? Why or why not? What sort of effects might this title have in our society?
4. In biology, the terms “resistance” and “immunity” have different meanings. Resistance is a pre-existing mutation in an organism that confers protection against a threat or challenge such as a virus. “Resistance” is used in the same manner as “antibiotic-resistance” in bacteria. “Immunity” refers to an active response of the immune system to the challenge of foreign particles that confers protection upon the organism. You have investigated many forms of protections against HIV. Which of these constitute resistance and which of them constitute immunity?

References

- Ahmad, Nafees (2002). *HIV and Its Coreceptors*. Dept. of Microbiology and Immunology, Honors Biology 181 at The University of Arizona. <http://student.biology.arizona.edu/honors2002/group09/home09.html>. Accessed: 25 November 2009.
- Alimonti, J.B., Limani, J., Matu, L., Wachihi, C., Kaul, R., Plummer, F.A., et al. (2006). Characterization of CD8 T-cell responses in HIV-1 exposed seronegative commercial sex workers from Nairobi, Kenya. *Immunology & Cell Biology* 84(5): 482–485.
- Biasin, M., Caputo, S.L. Speciale, L., Columbo, F., Racioppi, L., Zagliani, A., et al. (2000). Mucosal and

- systemic immune activation is present in human immunodeficiency virus-exposed seronegative women. *Journal of Infectious Diseases* 182(5): 1365–1374.
- Biti, R., French, R., Young, J., Bennetts, B., Stewart, G., Liang, T (1997). HIV-1 infection in an individual homozygous for the CCR5 deletion allele. *Nature Medicine* 3: 252–253.
- Dragic, T., Litwin, V., Allaway, G.P., Martin, S.R., Huang, Y., Nagashima, K.A., Cayanan, C., Maddon, P.J., Koup, R.A., Moore, J.P., Paxton, W.A. (1996). HIV-1 entry into CD4+ cells is mediated by the chemokine receptor CC-CKR-5. *Nature* 381(6584): 667–673.
- Feng, Y. Broder, C.C., Kennedy, P.E., Berger. E.A. (1996). HIV-1 entry cofactor: functional cDNA cloning of a seven-transmembrane G protein-coupled receptor. *Science* 272: 872–877.
- Glass, W.G., McDermott, D.H., Lim, J.K., et al, (2006). CCR5 deficiency increases risk of symptomatic West Nile virus infection. *Journal of Experimental Medicine* 203(1): 35–40. Retrieved 4 February 2010 from <http://jem.rupress.org/cgi/content/abstract/203/1/35>.
- Goldberg, D.G., Green, S.T., Kennedy, D.H., Emslie, J.A., Black, J.D. (1988). HIV and orogenital transmission. *Lancet* 2: 1363.
- Hasselrot, K., Saberg, P., Hirbod, T., Soderlund, J., Ehnlund, M., Bratt, G., et al. (2009). Oral HIV-exposure elicits mucosal HIV-neutralizing antibodies in uninfected men who have sex with men. *AIDS* 23: 329–333.
- Hirbod, T., Kaul, R., Reichard, C., Kimani, J., Ngugi, E., Bwayo, J.J., et al. (2008). HIV-neutralizing immunoglobulin A and HIV-specific proliferation are independently associated with reduced HIV acquisition in Kenyan sex workers. *AIDS* 22: 727–735.
- Jeffreys J. (April 2006). Co-receptor Conundrum. Treatment Action Group (Tagline). The Body.com: The Complete HIV/AIDS Resource. <http://www.thebody.com/content/art1756.html> Accessed: 4 February 2010.
- John, R., Arango-Jaramillo, S., Finny, G.J., Schartz, D.H. (2004). Risk associated HIV-1 cross-clade resistance of whole peripheral blood mononuclear cells from exposed uninfected individuals with wild-type CCR5. *Journal of Acquired Immune Deficiency Syndromes* 35(1): 1–8.
- Kaul, R., Plummer, F.A., Kimani, J., Dong, T., Kiama, P., Rostron, T., et al. (2000). HIV-1 specific mucosal CD8+ lymphocyte responses in the cervix of HIV-1-resistant prostitutes in Nairobi. *Journal of Immunology* 164(3): 1602–1611.
- Kaul, R., Dong, T., Plummer, F.A., Kimani, J., Rostron, T., Kiama, P., et al. (2001a). CD8+(+) lymphocytes respond to different HIV epitopes in seronegative and infected subjects. *Journal of Clinical Investigation* 107(10): 1303–1310.
- Kaul, R., Rowland-Jones, S.L., Kimani, J., Dong, T., Yang, H.B., Kiama, P., et al. (2001b). Late seroconversion in HIV-resistant Nairobi prostitutes despite pre-existing HIV-specific CD8+ responses. *Journal of Clinical Investigation* 107(3): 341–9.
- Kebba, A., Kaleebu, P., Rowland, S., Ingram, R., Whitworth, J., Imami, N., et al. (2004). Distinct patterns of peripheral HIV-1-specific interferon-gamma responses in exposed HIV-1-seronegative individuals. *Journal of Infectious Diseases* 189(9): 1705–1713.
- Lo Caputo, S., Trabattoni, D., Vichi, F., Piconi, S., Lopalco, L., Villa, M.L., et al. (2003). Mucosal and systemic HIV-1-specific immunity in HIV-1-exposed but uninfected heterosexual men. *AIDS* 17(4): 531–539.
- Liu, R., Paxton, W.A., Choe, S., Ceradini, D., Martin, S.R., Horuk, R., MacDonald, M.E., Stuhlmann, H., Koup, R.A., Landau, N.R. (1997). Homozygous defect in HIV-1 coreceptor accounts for resistance of

some multiply-exposed individuals to HIV-1 infection. *Cell* 86: 367–377.

- Makedonas, G., Bruneau, J., Lin, H., Sekaly, R.P., Lamothe, F., Bernard, N.F. (2002). HIV-specific CD8+ T-cell activity in uninfected injection drug users is associated with maintenance of seronegativity. *AIDS* 16(12): 1595–1602.
- Martinson, J.J., Chapman, N.H., Rees, D.C., Liu, Y-T, Clegg, J.B. (1997). Global distribution of the CCR5 gene 32-basepair deletion. *Nature Genetics* 16: 100–103.
- O'Brien, T.R., Winkler, C., Dean, M., Nelson, J.A., Carrington, M., Michael, N.L., White, G.C. (1997). HIV-1 infection in a man homozygous for CCR5 delta 32. *Lancet* 349: 1219.
- Paxton, W.A., Martin, S.R., Tse, D., O'Brien, T.R., Skurnick, J., VanDevanter, N.L., Padian, N., Braun, J.F., Kotler, D.P., Wolinsky, S.M., Koup, R.A. (1996). Relative resistance to HIV-1 infection of CD4 lymphocytes from persons who remain uninfected despite multiple high-risk sexual exposures. *Nature Medicine* 2(4): 412–417.
- Pinto, L.A., Sullivan, J., Berzofsky, J.A., Clerici, M., Kessler, H.A., Landay, A.L., et al. (1995). ENV-specific cytotoxic T lymphocyte responses in HIV seronegative health workers occasionally exposed to HIV-contaminated body fluids. *Journal of Clinical Investigation* 96(2): 867–76.
- Rowland-Jones, S.L., Nixon, D.F., Aldhous, M.C., Gotch, F., Ariyoshi, K., Hallam, N., et al. (1993). HIV-specific cytotoxic T-cell activity in an HIV-exposed but uninfected infant. *Lancet* 341(8849): 860–1.
- Rowland-Jones, S.L., Dong, T., Fowke, K.R., Kimani, J., Krausa, P., Newell, H., et al. (1998). Cytotoxic T cell responses to multiple conserved HIV epitopes in HIV-resistant prostitutes in Nairobi. *Journal of Clinical Investigation* 102(9): 1758–65.
- Sabeti, P.C., Walsh, E., Schaffner, S.F., Varilly, P., Fry, B., Hutcheson, H.B., Cullen, M., Mikkelsen, T.S., Roy, J., Patterson, N., Cooper, R., Reich, D., Altshuler, D., O'Brien, S., Lander, E.S. (2005). The case for selection at CCR5-Delta32. *PLoS Biology* 3(11): e378.
- Sampson, M., Libert, F., Doranz, B.L., Rucker, J., Liuesnard, C., Farber, C-M., Saragosti, S., Lapoumeroulie, C., Cognaux, J., Forceille, C., et al. (1996). Resistance to HIV-1 infection in caucasian individuals bearing mutant alleles of the CCR-5 chemokine receptor gene. *Nature* 382: 722–725.
- Wallace, J. (2009). HIV Resistance Through Oral Sex. PopSci. <http://www.popsci.com/scitech/article/2009-02/hiv-resistance-through-oral-sex>. Accessed: 27 November 2009.
- Yang, O.O., Boscardin, W.J., Matud, J., Hausner, M.A., Hultin, L.E., Hultin, P.M., et al. (2002). Immunologic profile of highly exposed yet HIV type 1-seronegative men. *AIDS Research and Human Retroviruses* 18(14): 1051–1065.



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