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The Ethics of Exponential Life Extension through Brain Preservation

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Abstract

Chemical brain preservation allows the brain to be preserved for millennia. In the coming decades, the information in a chemically preserved brain may be able to be decoded and emulated in a computer. I first examine the history of brain preservation and recent advances that indicate this may soon be a real possibility. I then argue that chemical brain preservation should be viewed as a life-saving medical procedure. Any technology that significantly extends the human life span faces many potential criticisms. However, standard medical ethics entails that individuals should have the autonomy to choose chemical brain preservation. Only if the harm to society caused by brain preservation and future emulation greatly outweighed any potential benefit would it be ethically acceptable to refuse individuals this medical intervention. Since no such harm exists, it is ethical for individuals to choose chemical brain preservation.

Introduction

One essential part of the definition of life is the drive to preserve existence. Thus it is not surprising that life extension has been a key concern of humanity throughout recorded history (Cave 2012). In the recent past, extending the human life span beyond the "natural" limit was seen as selfish, dangerous, and immoral (Fukuyama 2002; Kass 2003; President's Council on Bioethics 2003; Pijnenburg and Leget 2006; Blow 2013). However, a new generation of ethicists and scientists has challenged these views and shown that arguments against life extension do not hold up well to serious scrutiny (Bostrom 2005a; Bostrom 2005b; de Grey 2005; Horrobin 2005; Cutas and Harris 2007; Moen 2015). There is also a growing component of the general public with renewed faith in the progress of technology who are challenging traditional views of aging (Bostrom 2006; Cave 2012).

Together these two trends suggest that society may be more accepting of revolutionary approaches to life extension. The rapid advance of these technologies also makes it imperative to engage in a serious ethical discussion before they are implemented.

In the late 1980s, two visionary thinkers – Drexler (1987) and Olson (1988) – simultaneously proposed the hypothesis of chemical brain preservation. To understand chemical brain preservation we need to begin with cryonics. The idea of cryonics (freezing the body and brain) to suspend life until treatment can be provided has been around for at least a few hundred years (Cave 2012).[1] However, modern cryonics is based on a more sophisticated understanding of death. In the past, death was defined as cardiac arrest (cessation of a heartbeat), but modern resuscitation techniques have made this definition outdated. The current medical definition of death is based on the cessation of electrical activity in the cerebral cortex (National Conference of Commissioners on Uniform State Laws 1980; Whetstine et al. 2005). This definition is itself quickly becoming outdated with improvements in neurology and neurosurgery (Thomson 2014). In his discussion of cryonics, Merkle states:

> If the structures in the brain that encode memory and personality have been so disrupted that it is no longer possible in principle to recover them, then the person is dead. (1992, 9)

This is known as the information-theoretic definition of death and appears to be the ultimate definition of irreversible death. It provides the theoretical basis of cryonics: preserving the information in the brain until a time when the person's injuries are able to be treated. Thus cryonics is meant to be a life-saving medical procedure. The main limitation of current cryonics is that it is uncertain whether the information in the brain is truly preserved. This is at least partly due to the unjustified abandonment of cryonics by the scientific community.[2] Lack of funding is preventing the research needed to improve the protocols and fund electron microscopy studies needed to examine the integrity of the brain after preservation. Nonetheless, there is indirect evidence that cryonics as currently practiced may preserve the information in the brain which could then be theoretically recovered. Meon (2015) has convincingly argued that even if the chances of success are low, cryonics is still a rational choice that individuals should be allowed to make. Now we are ready to return to the proposals of Drexler and Olson.

Chemical brain preservation as life extension

Drexler (1987) and Olson (1988) showed that, when the information-theoretic definition of death is accepted, cryonics is only one of many techniques of life extension by information preservation. In chemical brain preservation, rather than using low temperatures to lock the brain in place, the brain is placed in stasis by chemical bonding (Drexler 1987; Olson 1988). This is known as plastination (Knott et al. 2008; Hayworth 2012).[3] The current protocols for chemical brain preservation were developed to preserve tissues for electron microscopy and they continue to improve (Palay et al. 1962; Olson 1988; Knott et al. 2008; Hayworth 2012; Mikula and Denk 2015).

Electron microscopy requires tissues to be cut extremely thin, and thus requires strong chemical bonding to avoid the breakup of tissue. Chemical preservation involves first infusing the vascular system with paraformaldehyde and glutaraldehyde, which fixes cellular proteins in place and prevents degradation. Next, lipids are fixed in place by infusing the tissue with osmium tetroxide, and finally the tissue is immersed in a plastic resin (Palay et al. 1962; Hayworth 2012). Once this procedure is complete the tissue is essentially embedded in plastic and completely preserved (think of insects trapped in amber). Electron microscopy studies have demonstrated that plastination does a remarkable job of preserving the brain (Knott et al. 2008; Hayworth 2012). In fact, modern chemical preservation does such a good job preserving the cellular and molecular structure that life can truly be frozen in this state. The tissue can be stored at room temperature without degradation and presumably could be preserved intact for millions of years. The main limitation of current brain preservation protocols is that they are limited to only a small section of the brain (Hayworth 2012). However, the protocols are rapidly advancing and there is an incentive price to scale up the preservation protocols to allow the

chemical preservation of a large mammalian brain (Hayworth 2012; Brain Preservation Foundation – Tech Prize n.d.; Brain Preservation Foundation – Announcement n.d.).

Starting in the mid-nineteenth century, systematic brain lesion studies have convincingly shown that the brain is completely responsible for the mind. The last two decades have seen a revolution in our understanding of how this is achieved. It turns out that identity is completely defined by anatomy: that is, brain connectivity (Sporns, Tononi, and Kötter 2005; Hayworth 2012; Yang, Pan, and Gan 2009; Honey, Thivierge, and Sporns 2010; Seung 2011; Seung 2013). Our memories and personalities are captured in the synaptic and dendritic connections in the brain, what is referred to as the connectome. The connectome contains all the information that matters for identity and consciousness connectivity (Sporns, Tononi, and Kötter 2005; Hayworth 2012; Yang, Pan, and Gan 2009; Honey, Thivierge, and Sporns 2010; Seung 2011; Seung 2013). Each night the specific electrical impulses that generate the stream of consciousness stop and you are stored as physical structure! The connectome reboots the stream of consciousness each morning and identity continues. Cases of revival after hypothermia (which is also now intentionally induced in trauma patients and stops all electrical activity in the brain) counter arguments that there is always some low level of consciousness, occurring even during deep sleep, that is required for identity to continue (Bolte et al. 1988; Thomson 2014). These cases also challenge the often unarticulated assumption that some kind of continual material or electrical circulation is required for identity to continue. Together the information theory of death and our new understanding of the connectome imply that death does not occur until the information in the connectome is irreversibly lost.

Suppose that chemical brain preservation is successful in preserving the connectome. In the past it was pure speculation that somehow preserved brains could be resuscitated using unknown nano-technology:

> In the distant future (e.g., 100 centuries from now), technology may advance to the state where the information of an individual's brain design can be extracted from his or her preserved brain and implanted in a new machine – the new brain of the individual. (Olson 1988, 79)

It is a testament to the exponential growth of technology that in contrast to Olson's prediction of 100 centuries, the technology now exists to extract the information from a preserved brain. It turns out that not only is electron microscopy a key tool to verify the preservation of the connectome, it is also a key part of the technology for extracting the information. The best current methods of brain mapping involve scanning thin slices of a chemically preserved brain with an electron microscope. Standard resolution is around 50 nm when the slices are created with a diamond knife (Hayat 2000). However, the newer technique of Focused Ion Beam Scanning Electron Microscopy (FIBSEM) is able to scan tissue at resolutions approaching 5 nm (Hayworth 2012; Hayworth 2015). The detail of all the synaptic and dendritic connections and their strengths can be captured at a resolution between 40 and 10 nm (Knott et al. 2008; Hayworth 2012). Even if the details at the molecular level (neurotransmitter and receptor levels) were necessary, this information is stored in the chemically preserved brain and there is ongoing research and a variety of promising techniques in development that can likely provide molecular level scanning resolution (Sandberg and Bostrom 2008). Continued progress in automated brain mapping techniques should allow the complete connectome to be obtained from preserved brains (Mishchenko 2009; Jain et al. 2010).

The next key piece of technology in making chemical brain preservation a life-saving procedure is whole brain emulation (WBE) (also known as mind uploading). WBE involves replicating the informational structure of the brain in software that could then be run in a computer (Sandberg and Bostrom 2008; Eth, Foust, and Whale 2013; Sandberg 2013). WBE is now big science (Markram 2006; Van Horn and Toga 2014; Human Brain Project n.d.). Knowledge of the connectome should allow for a complete emulation of brain function, and the technologies for mapping the connectome and for WBE have been advancing rapidly (Denk and Horstmann 2004; Markram 2006; Mishchenko 2009; Jain et al. 2010; Eliasmith et al. 2012; Zador et al. 2012; Helmstaedter et al. 2013; Yook,

Druckmann, and Kim 2013). The development of WBE and the computer technology to implement it is now a flagship science initiative of the European Union known as the Human Brain Project (Human Brain Project n.d.). This project aims to develop a complete emulation of a mouse brain within five years (Human Brain Project SP1 n.d.). Other than scale, there is no in-principle difference involved in human WBE. The Human Brain Project aims to scan and upload a significant portion of the human brain within ten years (Human Brain Project SP2 n.d.). Estimates vary, but we may be within 50 years of human WBE (Kurzweil 2005; Eth, Foust, and Whale 2013; Sandberg 2013). One important concern remains: will brain preservation followed by WBE preserve identity or even consciousness? These philosophical questions are outside the main scope of this paper, but there are good arguments that WBE does preserve identity and consciousness (Lewis 1976; Parfit 1984; Gallois 2005–2011; Hayworth 2010; Wiley 2014; Cerullo 2015).

Brain preservation and the individual

Before talking about the ethical arguments for or against brain perseveration we need to clear up some confusion in terminology. The terms radical or extreme life extension have been used in the past to describe a major increase in the human lifespan (Blow 2013; Masci 2013; Samuel 2013). These terms are unsatisfactory as they may have a negative connotation for many people. Considerable life extension is another proposed term (Rantanen 2013). While lacking the negative connotation of the previous terms it seems too vague; after all, some would consider five years of life extension considerable. Therefore, I propose the term exponential life extension. Exponential life extension can be defined as increases in life expectancy and/or life span by 50 per cent or more. Any discussion of exponential life extension also needs to touch on the common mistake of equating this with immortality (de Grey 2005; Horrobin 2005; Cave 2012). Immortality is a mythological concept and is not something that can be achieved with current life extension technologies (Horrobin 2005). Therefore, discussions of immortality are premature at this point and only serve as a distraction from the debate regarding more credible life extension technologies.

Now we can examine the ethical implications of brain preservation. First we will look at the ethical issues involving the individual, and in the next section we will examine arguments from a societal perspective. Is it ethically acceptable for an individual to chemically preserve their brain? Currently this isn't even a possibility, so we can rephrase this question as whether it is ethical for an individual to preserve their brain in the future when this becomes possible. A related question is whether it is ethical for individuals to research, and support research on, brain preservation.

I will assume for this discussion that the protocol used for brain preservation has been shown to preserve the connectome through clinical trials on human brains under realistic scenarios (i.e. the protocol starting minutes or more after brain death). We can also assume that the individual who chooses brain preservation is convinced that brain preservation followed by WBE will allow for the continuation of personal identity and consciousness. In this case, the individual correctly views brain preservation as a life-saving medical procedure. The option to choose (assuming a reasonable use of resources) or refuse medical procedures is a fundamental right of current medical ethics (Beauchamp and Childress 1977; Ad Hoc Committee on Medical Ethics, American College of Physicians 1984). Thus the default position should be to allow people to choose chemical brain preservation. To refuse to allow a person to choose this procedure would be a major affront to the principle of autonomy. The autonomy to choose brain preservation extends to the right to pursue and fund research into brain preservation. Standard medical ethics suggest that only evidence of serious harm to society could override a person's autonomy to pursue chemical brain preservation (Beauchamp and Childress 1977; Ad Hoc Committee on Medical Ethics, American College of Physicians 1984). Therefore, we need to examine arguments that brain preservation could be harmful to society, and this will be the focus of the next section.

Brain preservation and society

Medical ethics clearly supports a person's right to have or refuse a medical procedure that is deemed

scientifically sound. Thus we need to examine what potential harms brain preservation could have on society and determine whether these harms are enough to override a person's autonomy. The greatest ethical challenges to brain preservation concern issues of justice: will everyone be allowed to access these technologies or will they be only for the rich? One worry is that society will be dominated by a new oligarchy of those rich enough to afford brain preservation. However, this scenario seems very unlikely. The procedure to chemically preserve the brain is relatively straightforward and unlikely to cost more than a minor medical procedure (cost is in fact part of the requirement to win the brain preservation prize (Brain Preservation Foundation – Tech Prize n.d.)). The goal of those working on brain preservation is to have it recognized as a legitimate medical procedure that should be covered by both public and private insurance. The second step of WBE will likely be much more expensive. Yet WBE is an information technology that should follow the economics of scale. A good parallel is the history of the human genome project, another information technology. To sequence the first genome took 13 years and 3 billion dollars to complete (Gitlin 2013). However, gene sequencing technology gets cheaper every year and it may soon be possible to sequence individual genomes for a few hundred dollars (Metzker 2010; Mardis 2011; Gitlin 2013; Raj 2014). There will likely be a time, early in the development of the technology, when the cost of WBE will be too great for most people. Yet the early pioneers will help reduce the cost of WBE. Time is one thing those chemically preserved have plenty of, and they can wait for the economics of scale to reduce costs.

A related concern about the justice of brain preservation is the worry about limited resources. Is it right for people to continue to live past the "normal" life expectancy and take up resources that may not be available for the young? First, it should be noted that brain preservation could also be used on the young who would otherwise have died early. In this case, it is hard to see why the genetic lottery is a better way to decide who lives 20 years and who lives 90 years. Yet it is true that most people will likely be older when they choose brain preservation and there is a concern that there will a population explosion if the human life span is increased (Singer 1991; Kevles 1999; Kass 2001; Glannon 2002). To a large extent these are open empirical questions. The world population is slowing, and the industrialized nations (including China, Europe, and Japan)[4] are facing severe population decline (Wilson 2004; Morgan and Taylor 2006; Zhavoronkov 2013). In fact, there may be a major economic crisis looming due to the rapid decrease in population of these nations, and this will likely be true of the rest of the world as it increases in development (Rae et al. 2010; Zhavoronkov 2013). Rapid advances in life-extension technology may, indeed, be needed to help the aging population continue to be productive (Rae et al. 2010; Zhavoronkov 2013).

Thus brain preservation and WBE, rather than being a drain on society, may be part of keeping future economies viable. Even if population trends change, society can always choose to delay the revival of preserved brains until such time as economic conditions allow. If these conditions never arrive, the outcome for the individual is no worse than not choosing brain preservation in the first place and anyone pursuing brain preservation should understand these risks. It is also worth mentioning that those revived with WBE need not take up any significant resources or space: if necessary, WBEs could be run in underground computing facilities in a location that allows cheap solar power (e.g. unwanted space in a desert).

Another concern is that there will be undue pressure on people to choose brain preservation. First, it is important to recognize that those developing the technology for brain preservation take it as fundamental that people have a right to refuse such procedures (this is ingrained in the Brain Preservation Foundation Bill of Preservation Rights (Brain Preservation Foundation – Our Vision n.d.). There is no reason to suppose that if brain preservation were allowed society would lose all respect for the autonomy and freedom of medical consent that we have now. There is still a legitimate worry that if brain preservation became widespread then many people would indeed feel great, though informal, pressure to choose this option. We can safely assume this will not be a concern early on, based on the limited number of people who have pursued cryonics. As more evidence builds up that brain preservation and WBE do preserve identity (i.e. as it is shown that WBE of larger mammals captures behavior), more people will likely choose brain preservation. When the first human is successfully emulated and reports being the same person, most people will likely recognize brain

preservation as preserving identity (Kurzweil 2005). At this point, people may indeed feel pressure from family and friends to also sign up for brain preservation when they die. However, most of the pressure will arise because people believe the technology works, and this can hardly be held against brain preservation. There are those today who refuse evidence-based medical care and their wishes are respected; there is no reason to believe the development of brain preservation will alter the existing freedom to opt out of medical care.

Finally, there is the worry that exponential life extension of any kind will not give the young their chance (Singer 1991). As discussed previously, however, empirical evidence is suggesting just the opposite. Life-extension technologies are needed to give the young the same opportunities as the previous generation by avoiding the economic burden of sustaining a working/retired ratio that is rapidly approaching one-to-one in industrialized nations (Zhavoronkov 2013). A related worry is the lack of distribution of wealth created by inheritance. This concern is more political than ethical and can, in principle, be addressed through legislation (e.g. taxing a certain percentage of a person's wealth when they are preserved). Currently, cryogenically frozen human beings are treated as anatomical donations and have no rights. Clearly this will become increasingly unacceptable as the evidence for brain preservation grows and the feasibility for WBE increases. This does not mean we must treat those in suspension as if nothing has changed legally. For example, it has been proposed that we could legislate just how much wealth those in a preserved state could choose to have in a trust fund for when they are revived, while the rest of their money could be treated as inheritance (Sandberg 2014). Thus these issues do not seem insurmountable.

Conclusion

We have seen that there is little reason to fear progress in brain preservation technologies; rather, there is every reason to be optimistic. Chemical brain preservation is not currently an option, but it is extremely likely that within only a few years whole brain preservation protocols with strong scientific support in favor of connectome preservation will be available for large mammalian brains. When this happens, chemical brain preservation should be viewed as a life-saving medical procedure. In another decade, if whole brain emulation is successfully demonstrated in mice, then there will be overwhelming evidence that chemical brain preservation is a reversible and life-saving medical procedure. It would require an extraordinary amount of evidence showing harm to society to outweigh an individual's autonomy to choose this procedure if it is available, and no such evidence exists. The public is becoming more and more sophisticated in understanding these technologies, and the old arguments against life extension are becoming increasingly stale. In his struggle to gain acceptance for anti-aging research Aubrey de Grey has noted:

> I mean only that the evolution of our morality over time seems – for whatever reason – reliably to follow a course of increasing internal consistency, and, in particular, when deviations from this consistency become too stark to ignore, ethical opinions that are more central tend to survive at the expense of less central ones. (de Grey 2005, 660)

Thus with ever increasing advances in science, anti-aging research and life extension will be seen by the public as increasingly acceptable. Brain preservation and whole brain emulation will likely take longer to become widely accepted, yet once whole brain emulations become routine in animals it will become increasingly inconsistent to argue against the use of these technologies to preserve life.

The hypothesis that we are our connectome is a revolutionary idea that will take time to assimilate. Yet each day our scientific understanding of the brain grows, and there is no turning back from this knowledge. We need to learn from the tragedy of mainstream science's abandonment of the cryonics community. Brain preservation and whole brain emulation need to remain within the respected domains of mainstream scientific research, and organizations such as the Brain Preservation Foundation have recruited a wide range of highly respected scientific advisors to insure the scientific community's involvement (Brain Preservation Foundation – People n.d.). It would be a great tragedy not to take advantage of these technologies when they become available. It is time to remove the

taboo from brain preservation technologies (including cryonics) and support a major research investment in these procedures.

Notes

1. Mary Shelley, the author of *Frankenstein*, wrote a short story in 1826 entitled "Roger Dodsworth: The Reanimated Englishman" about a man being revived after being frozen in the Alps.

2. The story of modern cryonics is a tragic one of a legitimate scientific endeavor being abandoned by the scientific community (Darwin 1991; Cave 2012). A few brave souls continue to pursue cryonics, and this medical procedure is available today through two institutions (see Alcor n.d.; Cryonics Institute n.d.).

3. Newer forms of cryonics use a process called vitrification (Pichugin, Fahy, and Morin 2006; Fahy et al. 2009). Vitrification employs low temperatures and cryoprotectants to turn tissue into a glass-like state where decay is extremely slow. It is also possible to develop hybrid procedures involving elements of both cryonics and chemical brain preservation (McIntyre and Fahy 2015).

4. The birth rate in the United States is also down, but the population is stable largely due to immigration.

References

Ad Hoc Committee on Medical Ethics. 1984. American College of Physicians. American College of Physicians Ethics Manual. Part II: Research, Other Ethical Issues. *Annals of Internal Medicine* 101(2): 263–67.

Alcor. n.d. Alcor Life Extension website. http://www.alcor.org/ (accessed February 26, 2016).

Beauchamp T., and J. Childress. 1977. *Principles of biomedical ethics*. New York: Oxford University Press.

Blow C.M. 2013. Radical life extension. *New York Times*. August 7. http://www.nytimes.com/2013/08/08/opinion/blow-radical-life-extension.html?_r=0 (accessed February 26, 2016).

Bolte, R.G., P.G. Black, J.K. Thorne, and H.M. Corneli. 1988. The use of extracorporeal rewarming in a child submerged for 66 minutes. *Journal of the American Medical Association* 260: 377–79.

Bostrom, N. 2005a. The fable of the dragon-tyrant. *Journal of Medical Ethics* 31(5): 273–77.

Bostrom, N. 2005b. Recent developments in the ethics, science, and politics of life-extension. *Ageing Horizons* 3 (September/October): 28–33.

Bostrom, N. 2006. A history of transhumanist thought. *Journal of Evolution and Technology* 14(1) (June): 1–25. http://jetpress.org/volume14/bostrom.pdf (accessed February 26, 2016).

Brain Preservation Foundation – Tech Prize. n.d. Information regarding Brain Preservation Prize. http://www.brainpreservation.org/tech-prize/ (accessed February 26, 2016).

Brain Preservation Foundation – Announcement. n.d. Small Mammal BPF Prize Winning Announcement http://www.brainpreservation.org/small-mammal-announcement/ (accessed February 26, 2016).

Brain Preservation Foundation – People. n.d. BPF Advisory Board.
http://www.brainpreservation.org/content/advisors (accessed February 26, 2016).

Brain Preservation Foundation – Our Vision. n.d. Bill of Preservation Rights.
http://www.brainpreservation.org/preservation-rights/ (accessed February 26, 2016).

Cave, S. 2012. *Immortality: The quest to live forever and how it drives civilization*. New York: Random House.

Cerullo, M.A. 2015. Uploading and branching identity. *Minds and Machines* 25(1): 17–36.
http://link.springer.com/article/10.1007%2Fs11023-014-9352-8 (accessed February 26, 2016).

Cryonics Institute n.d. Cryonics Institute website. http://www.cryonics.org/ (accessed February 26, 2016).

Cutas, D., and J. Harris. 2007. The ethics of ageing, immortality and genetics. In *Principles of health care ethics,* 2nd ed.*,* ed. R. Ashcroft, A. Dawson, H. Draper, and J. McMillan, 797–802. Chichester, UK: Wiley.

de Grey, A.D.N.J. 2005. Life extension, human rights, and the rational refinement of repugnance. *Journal of Medical Ethics* 31: 659–63.

Darwin, M. 1991. Cold war: The conflict between cryonicists and cryobiologists. *Cryonics*. Orig. pub. in three parts: 12(6) (June): 4–14; 12(7) (July): 2–8; 12(8) (August): 5–7.
Available online via *Cryonics Magazine* archive:
http://www.alcor.org/CryonicsMagazine/archive.html (accessed February 26, 2016).

Denk, W., and H. Horstmann. 2004. Serial block-face scanning electron microscopy to reconstruct three-dimensional tissue nanostructure. *PLoS Biology* 2(11): e329.

Drexler, K.E. 1987. *Engines of creation: The coming era of nanotechnology*. London: Anchor.

Eth, D., J. Foust, and B. Whale. 2013. The prospects of whole brain emulation within the next half-century. *Journal of Artificial General Intelligence* 4(3): 130-52.

Eliasmith, C., T.C. Stewart, X. Choo, T. Bekolay, T. DeWolf, Y. Tang, and D. Rasmussen. 2012. A large-scale model of the functioning brain. *Science* 338: 1202–1205.

Fahy, G.M., B. Wowk, R. Pagotan, A. Chang, J. Phan, B. Thomson, and L. Phan. 2009. Physical and biological aspects of renal vitrification. *Organogenesis* 5(3): 167–75.
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2781097/ (accessed February 26, 2016).

Fukuyama, F. 2002. *Our posthuman future: Consequences of the biotechnology revolution*. New York: Picador.

Gallois, A. 2005–2011. Identity over time. *Stanford Encyclopedia of Philosophy (Summer 2012 Edition)*, ed. E.N. Zalta.
http://plato.stanford.edu/archives/sum2012/entries/identity-time/ (accessed February 26, 2016).

Gitlin, J.M. 2013. Calculating the economic impact of the Human Genome Project. National Human Genome Research Institute.
https://www.genome.gov/27544383 (accessed February 26, 2016).

Glannon, W. 2002. Identity, prudential concern, and extended lives. *Bioethics* 16(3): 266–83.

Hayat, M.A. 2000. *Principles and techniques of electron microscopy: Biological applications*. Cambridge: Cambridge University Press.

Hayworth, K.[J.] 2010. Killed by bad philosophy: Why brain preservation followed by mind uploading is a cure for death. Brain Preservation Foundation. http://www.brainpreservation.org/wp-content/uploads/2015/08/killed_by_bad_philosophy.pdf (accessed February 26, 2016).

Hayworth, K.J. 2012. Electron imaging technology for whole brain neural circuit mapping. *International Journal of Machine Consciousness* 4(1): 87–108.

Hayworth, K.J., C.S. Xu, Z. Lu, G.W. Knott, R.D. Fetter, J.C. Tapia, J.W. Lichtman, and H.F. Hess. 2015. Ultrastructurally smooth thick partitioning and volume stitching for large-scale connectomics. *Nature Methods* 12(4): 319–22.

Helmstaedter, M., K.L. Briggman, S.C. Turaga, V. Jain, H.S. Seung, and W. Denk. 2013. Connectomic reconstruction of the inner plexiform layer in the mouse retina. *Nature* 500: 168–74.

Honey, C., J.P. Thivierge, and O. Sporns. 2010. Can structure predict function in the human brain? *NeuroImage* 52: 766–76.

Horrobin, S. 2005. The ethics of aging intervention and life-extension. In *Aging interventions and therapies,* ed. S. Rattan, 1–28. Singapore: World Scientific Publishers.

Human Brain Project. n.d. Human Brain Project website. https://www.humanbrainproject.eu (accessed February 26, 2016).

Human Brain Project SP1. n.d. Human Brain Project Strategic Mouse Brain Data. https://www.humanbrainproject.eu/strategic-mouse-brain-data (accessed February 26, 2016).

Human Brain Project SP2. n.d. Human Brain Project Strategic Human Brain Data. https://www.humanbrainproject.eu/strategic-human-brain-data (accessed February 26, 2016).

Jain, V., H.S. Seung, and S.C. Turaga. 2010. Machines that learn to segment images: A crucial technology for connectomics. *Current Opinion in Neurobiology* 20: 653–66.

Kass, L. 2001. L'Chaim and its limits: Why not immortality? *First Things* 11: 17–24.

Kass, L. 2003. Ageless bodies, happy souls: Biotechnology and the pursuit of perfection. *New Atlantis* 1 (Spring): 9–28.

Kevles, D. 1999. Life on the far side of 150. *New York Times*, March 16. http://www.nytimes.com/1999/03/16/opinion/life-on-the-far-side-of-150.html (accessed February 26, 2106)

Knott, G., H. Marchman, D. Wall, and B. Lich. 2008. Serial section scanning electron microscopy of adult brain tissue using focused ion beam milling. *Journal of Neuroscience* 28(12): 2959–2964.

Kurzweil, R. 2005. *The Singularity is near: When humans transcend biology*. New York: Viking.

Lewis, D. 1976. Survival and identity. In *The Identities of Persons*, ed. A.O. Rorty, 17–40. Berkeley: University of California Press.

Marblestone, A.H, and E.S. Boyden. 2014. Designing tools for assumption-proof brain mapping. *Neuron* 83(6): 1239–1241.

Mardis, E.R. 2011. A decade's perspective on DNA sequencing technology. *Nature* 470: 198–203.

Markram, H. The Blue Brain Project. *Nature Reviews Neuroscience* 7(2):153–60.

Masci, D. 2013.To count our days: The scientific and ethical dimensions of radical life extension. Pew Research Center. August 16.
http://www.pewforum.org/files/2013/08/Life-Extension-Essay.pdf (accessed February 26, 2016).

McIntyre, R., and G. Fahy. 2015 Aldehyde-stabilized cryopreservation. *Cryobiology* 71(3): 448–58.

Merkle, R. 1992. The technical feasibility of cryonics. *Medical Hypotheses* 39: 6–16.

Metzker, M. 2010. Sequencing technologies – the next generation. *Nature Genetics* 11: 31–46.

Mikula, S., and W. Denk. 2015. High-resolution whole-brain staining for electron microscopic circuit reconstruction. *Nature Methods* 12(6): 541–46.

Mishchenko, Y. 2009. Automation of 3D reconstruction of neural tissue from large volume of conventional serial section transmission electron micrographs. *Journal of Neuroscience Methods* 176(2): 276–89.

Moen, O.M. 2015. The case for cryonics. *Journal of Medical Ethics*. Published online first February 25. doi:10.1136/medethics-2015-102715.
http://jme.bmj.com/content/early/2015/02/25/medethics-2015-102715 (accessed February 26, 2016).

Morgan, S., and M. Taylor. 2006. Low fertility at the turn of the twenty-first century. *Annual Review of Sociology* 1(32): 375–99.

National Conference of Commissioners on Uniform State Laws. 1980. *Uniform Determination of Death Act*.
http://pntb.org/wordpress/wp-content/uploads/Uniform-Determination-of-Death-1980_5c.pdf
(accessed February 26, 2016).

Olson, C. 1988. A possible cure for death. *Medical Hypotheses* 26: 77–84.

Palay, S.L., S.M. McGee-Russell, S. Gordon, and M.A. Grillo. 1962. Fixation of neural tissues for electron microscopy by perfusion with solutions of osmium tetroxide. *Journal of Cell Biology* 12: 385–410.

Parfit, D. 1984. *Reasons and persons*. Oxford: Clarendon Press.

Pichugin, Y., G. Fahy, and R. Morin. 2006. Cryopreservation of rat hippocampal slices by vitrification. *Cryobiology* 52: 228–40.

Pijnenburg, M.A.M., and C. Leget. 2006. Who wants to live forever? Three arguments against extending the human lifespan. *Global Medical Ethics* 33(10): 585–87.

President's Council on Bioethics. 2003. *Beyond therapy: Biotechnology and the pursuit of human improvement*. Washington, DC: Dana Press.

Rae, M.J, R.N. Butler, J. Campisi, A.D.N.J. de Grey, C.E. Finch, M. Gough, G.M. Martin, J. Vijg, K.M. Perrott, and B.J. Logan. 2010. The demographic and biomedical case for late-life interventions in aging. *Science Translational Medicine* 2(40): 40cm21.

Raj, A. 2014. Soon, it will cost less to sequence a genome than to flush a toilet – and that will change medicine forever. *Business Insider*. October 3. http://jme.bmj.com/content/early/2015/02/25/medethics-2015-102715 (accessed February 26, 2016).

Rantanen, R. 2013. Issues in the debate on the ethics of considerable life extension. *Res Cogitans* 1: 34–51.

Samuel, L. 2013. *Death, American style: A cultural history of dying in America*. Plymouth, UK: Rowman & Littlefield.

Sandberg, A., and N. Bostrom. 2008. *Whole Brain Emulation: A roadmap*. Future of Humanity Institute, Oxford University. http://www.fhi.ox.ac.uk/brain-emulation-roadmap-report.pdf (accessed February 26, 2016).

Sandberg, A. 2013. Feasibility of whole brain emulation. In *Theory and philosophy of artificial intelligence*, ed. V.C. Müller, 251–64. Berlin: Springer.

Sandberg, A. 2014. Ethics of brain emulations. *Journal of Experimental & Theoretical Artificial Intelligence* 26(3): 439–57. http://www.tandfonline.com/doi/pdf/10.1080/0952813X.2014.895113 (accessed February 26, 2016).

Seung, H.S. 2011. Towards functional connectomics. *Nature* 471:170–72.

Seung, [H.]S. 2013. *Connectome: How the brain's wiring makes us who we are*. New York: Houghton Mifflin Harcourt.

Singer, P. 1991. Research into aging: Should it be guided by the interests of present individuals, future individuals, or the species? In *Life span extension: Consequences and open questions*, ed. F. Ludwig, 132–45. New York: Springer.

Sporns, O., G. Tononi, and R. Kötter. 2005. The human connectome: A structural description of the human brain. *PLoS Computational Biology* 1(4): e42. http://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.0010042 (accessed February 26, 2016).

Thomson, H. 2014. Gunshot victims to be suspended between life and death. *New Scientist* 2962 (March 29): 8–9.

Van Horn, J.D., and A.W. Toga. 2014. Human neuroimaging as a "big data" science. *Brain Imaging Behavior* 8(2): 323–31.

Whetstine, L., S. Streat, M. Darwin, D. Crippen. 2005. Pro/con ethics debate: When is dead really dead? *Critical Care* 9: 538–42.

Wiley, K. 2014. *A taxonomy and metaphysics of mind-uploading*. Electronic ed. Seattle: Humanity+ Press and Alautun Press.

Wilson, C. 2004. Fertility below replacement level. *Science* 304: 207–209.

Yang, G., F. Pan, and W. Gan. 2009. Stably maintained dendritic spines are associated with lifelong memories. *Nature* 462(17): 920–25.

Yook, C., S. Druckmann, and H. Kim. 2013. Mapping mammalian synaptic connectivity. *Cellular and Molecular Life Sciences* 70: 4747–4757.

Zador, A.M., J. Dubnau, H.K. Oyibo, H. Zhan, G. Cao, and I.D. Peikon. 2012. Sequencing the connectome. *PLoS Biology* 10(10): e1001411. http://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.1001411 (accessed February 26, 2016).

Zhavoronkov, A. 2013. *The ageless generation: How advances in biomedicine will transform the global economy*. New York: Palgrave Macmillan.