1 Introduction

The first sketch of ectogenesis appears in alchemical writings attributed to the Swiss philosopher, alchemist, physician, and theologian Paracelsus. Whilst his work on toxicology was highly influential on later developments in medicine, the model of ex utero gestation Paracelsus described in his *De natura rerum* is unlikely to have passed muster in any clinical trial:

> Let the semen of a man putrefy by itself in a sealed cucurbite with the highest putrefaction of the venter equinus [horse manure] for forty days, or until it begins at last to live, move, and be agitated, which can easily be seen . . . If now, after this, it is everyday nourished and fed cautiously and prudently with [an] arcanum of human blood . . . it becomes, thenceforth, a true and living infant, having all the members of a child that is born from a woman, but much smaller.[1]

It is unclear whether Paracelsus ever tried to grow himself a little homunculus in this manner – his writings on this subject are all methodology and no results. However, this manuscript stands out as one of the only musings on gestation outside the body in a catalogue of developmental biology stretching over several thousand years. Is this because nobody was interested, or because the idea was so far-fetched as to be dismissed as straightforwardly impossible?

Fast-forward to the present day: the artificial womb has been a renewed subject of interest and concern among bioethicists in recent years. Increasingly successful proof-of-principle trials using mid-to-late-gestational stage animal foetuses have been carried out in a number of countries, giving a factual basis to previously abstract notions familiar from mythology and science fiction. These developments have prompted new metaphysical and ethical questions about this hypothetical technology, as well as reinvigorating old debates. Authors have vied with one another to define the moral status and properties of the entity being gestated. Is it legally a child once removed from the womb? What if it was never in the (biological) womb to begin with, but began its existence in an artificial environment? Should we call it a foetus, a premature newborn, a gestateling? Similarly, we are faced with debates over the correct terminology to use to describe the process of development in an artificial environment: ectogenesis, ectogestation, and incubation. For now, we will start with the term *ectogenesis:*

> Strictly speaking, the roots of the words "ecto" (outside) and "genesis" (development), suggests that this literally means "development outside" – i.e. outside the body. But since that is the norm in most of the biological world, the focus in practice is on the development of placental mammals – specifically humans – outside the maternal body, where this development would normally happen inside.[2]

The term first appeared in writing a century ago, in a lecture on the science of the future presented by John Haldane in Cambridge. In his lecture, Haldane described a future society in which fewer than a third of children would be 'born of women', and the rest produced through artificial means. This society would be one in which only a small number of individuals, deemed sufficiently superior to their peers, would be 'selected as ancestors' for the following generation. Haldane imagined the view from the year 2074: 'Had it not been for ectogenesis there can be little doubt that civilization would have collapsed within a measurable time owing to the greater fertility of the less desirable members of the population in almost all countries'.[3] Less than a decade later, Haldane's contemporary Aldous Huxley published *Brave New World*.[4] In his satirical vision of the twenty-sixth century, ectogenesis is the ultimate in state reproductive and social control: human beings come into being in the Central Hatchery, pre-programmed for their role in society by the artificial wombs in which they grow. In both writers' visions of the future, the artificial womb (alongside other reproductive technologies, such as cloning) offers its users vastly improved control of foetal development, and by extension, of human progeny.

Complete ectogenesis is (of course) yet to be achieved: we cannot replace mammalian reproductive processes with artificial stand-ins from start to finish. Even if we wanted to attempt this, legal regulations prohibiting the cultivation of human embryos in vitro beyond a certain point of development would cut off such experimentation very early in the process. Ectogenic research must therefore be divided, at least for the time being, into work on early human development (fertilisation, implantation, organogenesis, etc.) and on partial ectogestation: interventions for the benefit of preterm foetuses in established pregnancies. Ectogestation – foetal development in an artificial environment, following removal from a biological womb – is not simply another kind of incubator. As Elselijn Kingma and Suki Finn explain, a crucial defining characteristic of ectogestation is 'development after being "born-by-location-change" but before being "born-by-physiology-change": i.e. development outside the maternal body that prevents the physiological transformation from foetus to neonate'.[5] They outline some of the key differences between foetal and neonatal physiology:

> Most obviously, foetuses do not breathe but oxygenate their blood via the placenta. This results in different normal arterial and venous oxygen tensions compared to neonates; requires a different kind of haemoglobin; and so on. It also necessitates a completely different cardiovascular set-up: the foetal heart functions as a single (rather than, in neonates, a double) pump; and the cardiovascular system in foetuses compared to neonates has multiple shunts, different flow rates and blood pressures in different parts of the system, and so on.[6]

In Sections 2–5 of this Element, I give an overview of the stories that people tell about ectogenesis. Some of these offer moral, scientific and political rationales for developing and using artificial womb technology; some warn that this would have adverse outcomes, and that we should therefore avoid it. In Section 6, I focus on a particular idea put forward by a number of bioethicists in the last few decades, which I refer to as the Convergence Argument. This is a hypothesis that purports to avoid some of the ethical problems associated with the development of complete ectogenesis, by suggesting that this technology could be developed almost coincidentally through the convergence of the two branches of scientific research differentiated earlier. In the second half of this Element, I aim to show that this Convergence Argument – like many of the stories told about ectogenesis by bioethicists, legal scholars, feminist activists and others over the last half-century – is divorced in important ways from the actual state of biomedical science in this field.

Sections 7–10 therefore focus on this research: I examine developments in embryology, in reproductive interventions, neonatal intensive care, and animal ectogestation, outlining key developments over the last century. In Sections 11–13, I turn my attention to the most cutting-edge developments in ectogestation and the possibility of first-in-human trials of this technology. I highlight the practical and ethical questions that such a prospect demands to be addressed. Finally, in Sections 14–16, I consider some of the presuppositions upon which the Convergence Argument rests with regard to the extension of in vitro culture of embryonic/foetal research subjects. Drawing comparisons with the development of technologies such as in vitro fertilisation (IVF) and mitochondrial DNA (mtDNA) transfer, I consider the circumstances under which it may be ethically permissible to bring children into the world for the purposes of research. Is it ethical to create life to show that it can be done?

2 Beyond Barbarism

Here is one story that people tell about ectogenesis: ‘Pregnancy is dreadful. Really dreadful, it plays havoc with your body – what, yes, and childbirth too, even worse! The things it does to people. My wife/ colleague/ sister-in-law/ neighbour had an emergency caesarean/ pre-eclampsia/ post-partum depression. Pregnancy comes for women’s appetites, their moods, their libidos, their energy – and then childbirth finishes them off! These natural processes are barbaric. But artificial wombs would rescue us from this torture. No one would ever have to go through this again’.

Much of this might sound like hyperbole, but such attitudes are founded on real enough problems. Although some people have relatively comfortable pregnancies and deliver their children without complications, those complications are common. One study found that nearly half of all pregnant women in the United States experienced at least one unexpected complication.[7] Even when women were divided by risk group, unexpected complications occurred in 29 per cent of low-risk pregnancies. During pregnancy, 70–80 per cent of women experience nausea and vomiting ('morning sickness'), which in turn has significant impacts on daily functioning, emotional well-being, vitality, and mental health.[8] Eighty-five per cent of women experience perineal injury during childbirth, with spontaneous perineal laceration (tearing) occurring in one-third of births.[9] About one in four children in the United Kingdom are delivered through caesarean section ('C-section'), which, although it may spare a woman the 'trial' of vaginal delivery, is nonetheless itself a major abdominal surgery carrying a number of health risks and requiring a lengthy recovery period. This recovery period will often not be granted to the postnatal patient, who is normally expected to care for her infant, even whilst still on the ward.[10] In some cases, C-section is carried out as an elective operation; in others, it is recommended due a foetus' breech position, or due to maternal conditions such as placenta praevia (in which the placenta is partially or totally covering the cervix) or pre-eclampsia (high blood pressure which, if left untreated, can result in life-threatening fits called eclampsia). C-section rates have been rising steadily in the United Kingdom, and are already significantly higher (and continuing to rise) in a number of countries including Brazil, Turkey, Cyprus, China, Italy, and Mexico.[11] However, the global upward trend in C-sections has been met with concern from some, given its strong correlation with non-medical factors such as economic gain on the part of hospitals, fear of litigation on the part of healthcare providers, and fear of vaginal delivery on the part of mothers.[12]

The last few decades have seen growing concern regarding the extent and manner of medical intervention in obstetrics. For example, the overuse of interventions such as C-section and episiotomy in the absence of medical indication has been described as a symptom of the 'over-medicalisation' of childbirth.[13] Research points to trends of 'too much too soon' treatment, including 'unnecessary use of non-evidence-based interventions, as well as use of interventions that can be life-saving when used appropriately, but harmful when applied routinely or overused'.[14] We must also acknowledge the growing corpus of work demonstrating a substantial undercurrent of misogyny, coercion and control in reproductive and obstetric care. Individual activists, non-governmental organisation, and researchers have

brought to light widespread failures to seek or respect normal standards of informed consent in obstetric care.[15] One global review found that women across low-, middle-, and high-income countries reported experiences of physical and verbal abuse by healthcare providers during childbirth; it further found that women 'overwhelmingly felt "removed" from decisions about their childbirth, and that health workers were coercive and rushed through their deliveries in an attempt to reduce them to dependent, disempowered, and passive patients'.[16] The intersection of racism and misogyny in medicine has resulted in further burdens on black women, whose rates of maternal mortality are disproportionately high in the United Kingdom, United States, and other developed countries.[17] Finally, normative stereotypes of maternity and what constitutes 'good' childbirth result in psychological barriers to women's own advocacy for their needs. As Evie Kendal observes, 'Although it would seem unreasonable to expect someone suffering the debilitating cramps associated with appendicitis to forego pain relief, women still report feelings of guilt when requesting analgesia during labour'.[18]

We should be clear that there are several different (albeit connected) problems here. One is the mistreatment of women in reproductive healthcare; this was recently recognised by the United Nations Special Rapporteur on Violence Against Women as 'part of a continuum of the violations that occur in the wider context of structural inequality, discrimination and patriarchy'.[19] The other problem is the over-medicalisation of pregnancy and labour, together with widespread failures to respect ordinary medical standards of patient autonomy and informed consent. Finally, we have what appears to be the basic problem that biology has dealt humans – like other mammals – an unfortunate card when it comes to reproduction. In particular, nature has been rather cruel to the female half of the mammalian population, on whom most of the burdens fall.

Only the most evangelical stick to the old narratives about Eve's curse; there are various evolutionary explanations for the painful and dangerous mode by which we make new humans.[20] The difficulties women face in pregnancy and childbirth have often been characterised in a way that suggests this is a uniquely human problem, with reference to the 'obstetrical dilemma' hypothesis: walking upright on two legs makes a narrow pelvis most efficient, whereas giving birth (safely) to babies with large brains demands a wide pelvis. This is, however, a hypothesis that has been challenged on various empirical and theoretical grounds in recent years.[21] Although the few observations available indicate that childbirth generally takes more time and work in humans than in some non-human primates, there are few comparative studies of labour and

delivery in these primates, and therefore little data to substantiate the view that humans are alone in problematic parturition.[22] The hypothesis also does not bear up against comparison with some other mammals with whom we live in close proximity, and in whom our greater economic vested interest *has* driven some (albeit still limited) data collection: livestock. The results of a number of Australian publications, summarised in 2014, conclude that an average of 20–30 per cent of lambs die prior to weaning, with dystocia (a long and difficult birth demanding assistance) listed as one of the major causes of mortality.[23] Annual ewe mortality 'has been estimated at 2–10 per cent in New Zealand and Australia, with higher susceptibility in multiple-bearing ewes'.[24]

However academically interesting these comparisons might be, they provide little comfort for those who are currently suffering with pregnancy or birth-related conditions, or who live with lingering health problems or trauma from previous births. Whatever the reason that pregnancy and childbirth came to be this way, the myriad risks and burdens they represent have not yet been solved by modern medicine. These problems are tightly connected – not just to each other, but also to the wider structures and narratives within which we find the mythology of ectogenesis taking shape. We will come back to these later – for now, suffice it to say that biological reproduction is a risky business. One story says: that artificial wombs would let us avoid all of these problems, either by allowing a biological pregnancy to be transferred to an artificial womb when things go wrong (partial ectogestation – see Section 6) or by sidestepping the body altogether and using the artificial womb from start to finish (complete ectogenesis).[25] But once we imagine that we can replace the 'brutality' of biological gestation with a technological alternative, further motivations follow. For one thing, as I discuss in the next section, many authors have raised the point that it is not only women who could benefit from the 'mother machine'.

3 Mother Machines

The rationale for developing ectogenesis appears to branch at this point: we can make a distinction between *ectogestation as medical treatment* and *ectogenesis as (re)productive facility.* The former would allow us to step in when an existing pregnancy begins to 'go wrong', ending the biological pregnancy but continuing to gestate the foetus. Here, depending on how we understand the metaphysics and ethics of pregnancy, we either have one patient, the pregnant woman; or (if we recognise the foetus as a distinct patient) we have two patients.[26] Either way, there are specific and identifiable health interests that can guide and justify medical intervention; we come back to

this point in more detail in Section 12. The latter – ectogenesis as a reproductive facility – would not intervene in or assist with an existing human pregnancy and childbirth, but would replace these processes from 'day one', as an alternative to biological baby-making.

This distinction can be slotted into a larger debate about assisted reproduction. In the surrogacy industry, we already find a blurring of lines between bodily function, human labour, and social role, with the production of children entirely detached from their rearing. We might think that this is a pathway leading naturally, inevitably, towards the pursuit of artificial womb technology. Writing for *The Guardian* in 2002, social theorist Jeremy Rifkin espouses precisely this view: 'Thousands of surrogate mothers' wombs have already been used to gestate someone else's fertilised embryos. The artificial womb seems the next logical step in a process that has increasingly removed reproduction from traditional maternity and made of it a laboratory process'.[27] Of course, it is quite a leap from surrogate pregnancy to ectogenesis. The former (which is, after all, simply 'normal' biological pregnancy with a donated egg or embryo) may remove reproduction from traditional maternity, but the latter removes reproduction from the human body. Separating social roles from biological processes is, it is fair to assume, a sight easier than separating biological processes from the biological organism. But technological difficulties aside, we can understand *ectogenesis as reproductive facility* as part of the same story as surrogacy: one in which we are not necessarily talking in terms of medical treatment and patient interests, but in terms of social roles, prospective parents, the desire for a child of one's own.

As I have argued elsewhere, although childlessness may be deeply distressing, it is not itself a disease.[28] Infertility may sometimes be the result of some identifiable pathology, of course, but IVF and surrogacy do not resolve the cause of infertility to allow reproduction; rather, they circumvent the cause to provide couples or individuals with a child. The artificial womb as a reproductive facility, just as in the case of surrogacy, is differentiated from a curative or preventive project like those discussed in the last section. Recent work in bioethics has also pointed to the reproductive opportunities that ectogenic technology might bring: to LGBTQ+ individuals and couples for whom family-making with their chosen partners presents practical challenges, and to single men and infertile couples who would otherwise seek to have a child through surrogacy. This has been highlighted by some as a significant motivation for the pursuit of ectogenesis as an alternative route to parenthood.[29]