Narrative Review Article

How have Biomedical Engineering Advancements Shaped the Development of Contraceptive Devices from the 19th Century to the Present?

Aleena S. Khokhar

Lahore Grammar School Defence, 136 St 59, Block E Phase I Sector E, Defence Housing Authority, Lahore, Punjab, 54000, Pakistan

ABSTRACT

Contraception has undergone significant transformation throughout the years, evolving from rudimentary trial-and-error methods to contemporary bio-integrated technologies that shape reproductive autonomy and global health. This review traces the evolution from initial barrier methods and intrauterine devices (IUDs) to hormone delivery systems, with the emergence of implants, vaginal rings, and advanced contraceptive technologies. Analyzed from medical, technological, and social perspectives, it illustrates how scientific innovation, improved healthcare infrastructure, and supportive policies have expanded access to family planning while influencing individual future aspirations. In the future, emerging technologies such as multipurpose preventative technologies (MPTs), bioinformatics, and artificial intelligence (AI) may enhance the personalization, equity, and accessibility of birth control. Ultimately, the history of birth control reflects not only biomedical advances but also the ongoing global struggle for gender equality, reproductive rights, and health equity.

Keywords: Contraception; Reproductive Health; History of Contraception; Family Planning

INTRODUCTION

According to a 2023 World Health Organization (WHO) report, an estimated 257 million women globally lack access to modern contraceptive techniques (1). Ensuring access to these treatments is a vital right of women, enabling them to make independent choices regarding their bodies and maintaining equality. A woman is entitled to the liberty to obtain contraception free from any type of prejudice as the provision of such methods guarantees improved health outcomes for women (2). The use of contraception leads to a decrease in unplanned pregnancies and the necessity for abortions which is critically significant given that global estimates indicate over 600,000 women die annually from pregnancy-related complications, and 75,000 fall victims to unsafe abortions. It is estimated that at least 200,000 of these maternal fatalities could be prevented with adequate contraceptive care (3).

In addition to reducing mortality, contraception also mitigates the risk of psychological complications for mothers, as unintended pregnancies can result in nonpsychotic severe depression, particularly postpartum depression, as well as feelings of helplessness, heightened time constraints, and a decline in overall physical well-

Corresponding author: Aleena S. Khokhar, E-mail: aleena.s.khokhar@gmail.com.

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being. Broader access to contemporary contraception methods has not only benefited women but has contributed to better outcomes for children. For instance, global infant mortality has declined substantially over the past several decades, from approximately 150 fatalities per 1,000 live births in the 1950s to about 80 per 1,000 in the 1990s, illustrating the broader health advantages of family planning (3).

Access to contraception is not only beneficial for women, but it is also essential for the growth and development of a nation. In addition to fostering economic growth, it serves to limit overpopulation, which in turn reduces the load on resources. According to estimates provided by the United Nations, every dollar invested in contraception saves between two to six dollars in public spending on services such as medical care, education, immunizations, and sanitation, indicating that contraception is highly cost-effective. Furthermore, access to reliable contraceptive methods enhances women's social and economic participation, empowering them to fully contribute to society (4).

This review examines the technological and engineering innovations that have driven the development of contraceptive devices, tracing their evolution from the early prototypes of the 19th century to today's advanced, smart, and bio-integrated solutions. The discussion begins with a historical overview of contraceptive technologies, followed by an analysis of key engineering breakthroughs that enabled safer and more effective devices. It then highlights the current landscape of modern contraceptives, including digital and bio-integrated approaches, and concludes by exploring future directions for innovation at the intersection of biomedical engineering and reproductive health.

HISTORICAL BACKGROUND

Fertility regulation has historically been influenced not only by scientific advancements but also by social and religious factors. Prior to the 20th century, contraception was often stigmatized and associated with unlawful sexual conduct. Widespread acceptance and accessibility for married couples began to emerge only in the early 1900s, marking a pivotal shift in the perception and use of contraceptive methods (5).

The earliest recorded method of contraception was coitus interruptus and was succeeded by the advancement of barrier techniques. Historical accounts from ancient Rome document the utilization of a goat's bladder as a protective sheath, whilst ancient Egyptian literature mentions vaginal pessaries composed of various materials. By the 17th century, condoms crafted from animal intestines were in use and were notably mentioned in the writings of Casanova (5).

Ancient medical documents, like the Ebers Papyrus (1550 BC) and the writings of Pliny, Dioscorides, and Soranus, as well as the texts of 10th-century Arabic physicians like Al-Razi, Ali ibn Abbas, and Avicenna, offer some of the oldest known allusions to contraceptive procedures. Accounts outline procedures that span from fundamental post-coital hygiene routines to the experimental use of chemicals such as honey, alum, or lactic acid, as well as cures that are more symbolic or ritualistic in essence. Additional references encompass the utilization of animal feces, pessaries and sponges, which in certain respects foreshadowed subsequent barrier methods (6).

Although many early contraceptive approaches were experimental, inconsistent, or based on cultural beliefs, most were largely ineffective and unsafe, but they established the foundation for the systematic advancement of contraception. Beginning in the 19th century, technological and engineering advancements commenced the transformation of these early concepts into scientifically validated and effective devices, signifying the onset of contemporary contraceptive innovation. This set the stage for the development of early mechanical and barrier methods, which became increasingly practical and accessible due to improvements in materials and design.

EARLY MECHANICAL AND BARRIER METHODS OF THE 19TH CENTURY

The early 19th century signified a pivotal moment in contraceptive development, not only historically but from an engineering perspective. Improvements in materials science, manufacturing processes, and ergonomic design transformed contraception from improvised, artisanal products into standardized biomedical devices.

A major breakthrough occurred with the vulcanization of rubber by Charles Goodyear and Thomas Hancock in the 1840s. Vulcanization stabilized natural rubber by introducing sulfur cross-links, increasing elasticity, durability, and temperature resistance. From an engineering standpoint, this innovation enabled reproducible mass production of condoms, diaphragms, and pessaries with predictable mechanical properties. Devices became less porous, more resilient, and safer, reducing breakage and improving barrier reliability. By

the 1870s, industrial manufacturing processes allowed these "rubbers" to shift from luxury goods to affordable, widely distributed products promoted for the prevention of sexual diseases and fertility regulation (7).

During the same period, female-controlled barrier technologies advanced as well. The cervical cap (Figure 1) was launched in Europe in 1838, intended to completely cover the cervix, while the diaphragm was advocated for prolonged usage by the 1880s. Their development marked early applications of ergonomic biomedical design, devices shaped to conform to cervical anatomy while maintaining comfort during extended wear. Despite being less reliable than subsequent contraceptive technologies, these devices marked a significant advancement in empowering women about reproduction (8).

In addition to physical barriers, post-coital methods like douching became popular after 1830. Initially constructed from horn or pewter, early syringes transitioned to hard rubber variants post-mid-century. In 1843, French obstetrician Maurice Éguisier developed a self-acting irrigator, which gained popularity due to its automatic functionality and stayed in production for several decades. Although the efficacy of these techniques is limited, their prevalent application indicates a preference for female-managed contraception and the growing influence of commercially produced items in routine reproductive management (7).

Collectively, these innovations demonstrate that the 19th century represented a shift from improvised or folk-based approaches to standardized, industrially manufactured contraceptives, establishing a crucial foundation for the biomedical advancements of the 20th century.

INTRAUTERINE DEVICES (IUDS) AND MATERIAL INNOVATION

The intrauterine device (IUD) (Figure 2) originated in early 20th-century Germany through the research of Dr. Richard Richter, who in 1909 described the first scientifically documented, physician-inserted contraceptive. His design was a silkworm gut ring which he shortened at the ends of the cervical os, also known as the cervical opening, to facilitate removal and inspection. However, medical concerns about ascending infection and prevailing moral objections to intrauterine manipulation, especially in an era before antiseptic safety was established, limited its acceptance (9). Nonetheless, Richter's invention marked an important transition from simple barrier devices to the development of technologically advanced contraceptive methods.

In the 1920s, Karl Pust proposed adding buttons and extensions to the silkworm-gut ring to hide the cervix, but his designs were not widely accepted. Richter's idea was improved by Berlin gynecologist Ernst Gräfenberg, who wrapped the silkworm-gut ring in fine silver wire. Gräfenberg's "ring" significantly reduced pregnancy rates to approximately 1.6% and became one of the first

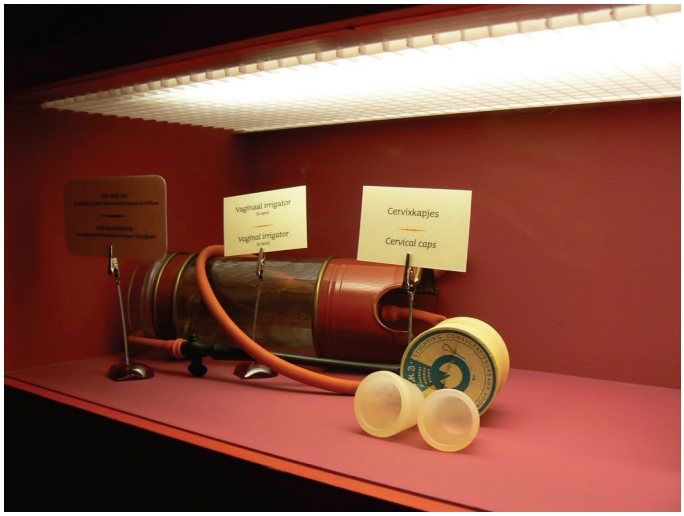

Figure 1. *Nineteenth-century female-controlled barrier devices, including cervical caps and vaginal irrigation instruments.*

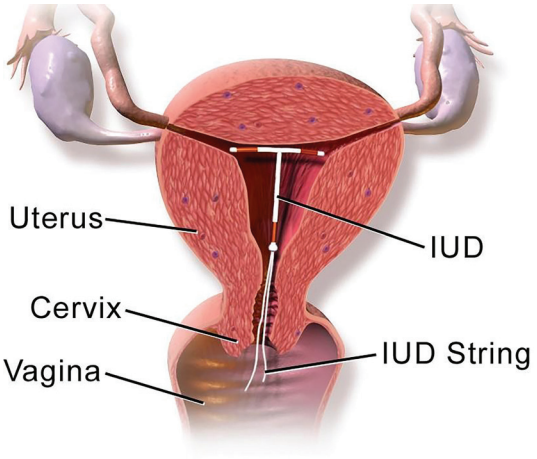

Figure 2. *Early intrauterine device (IUD) design illustrating the transition from rigid rings to flexible, biocompatible materials that improved insertion safety and infection control (25).*

intrauterine devices to undergo systematic scientific study. However, the gynecological community confused IUDs with stem pessaries and classified them as abortifacients. As a result, while reformists continued to recognize their potential, IUDs were largely disregarded by mainstream medicine for decades (9).

Despite initial reluctance within the medical community, the intrauterine device became involved in the interwar international sex reform movement. Using intrauterine contraception to regulate fertility without condoms was seen as a weapon for women's freedom. Reformers promoted the IUD not only as a medical innovation but also as a social development, linking it to suffrage and modernism initiatives (10). Medical conservatism contributed to the initial opposition to IUDs, driven by concerns about side effects, morality, and control over reproductive technologies, which delayed widespread acceptance despite scientific curiosity and emerging population policies (8). By the mid-20th century, replication studies conducted in Japan, Israel, and New York supported Gräfenberg's findings, especially after drugs reduced uterine infection fears (10).

The 1960s marked a turning point in the development of intrauterine devices, as advances in materials science and biomedical engineering addressed many of the limitations of earlier designs. Modern materials such as plastics and copper made intrauterine devices smaller, more flexible, and easier to insert and remove. In response to global demographic concerns, organizations like the Population Council promoted IUDs as scalable instruments for population control. What began as a marginal scientific project in Germany became a cornerstone of worldwide reproductive policy, spread widely in the Global South. (10).

The history of intrauterine contraception between 1900 and 1960 shows a pattern: medical conservatism initially opposed scientific curiosity, but global modernity and emerging population policies eventually embraced it. At the same time, material innovation drove progress, while episodes of corporate misconduct, and feminist health critiques ultimately undermined it.

HORMONAL DELIVERY SYSTEMS

The 1960s brought about an important development in birth control technology with the introduction of Enovid by G.D. Searle & Company, the first oral contraceptive approved by the U.S. Food and Drug Administration in 1960 and it represented one of the earliest large-scale applications of pharmacokinetics in reproductive medicine.

Before Enovid, women were limited to choosing between barrier methods or improvised remedies, which gave them less autonomy in fertility management. Supported by advocates like Margaret Sanger, Enovid signified a key advancement: a hormonal- based approach that directly empowered women to regulate reproduction (11). The initial formulation, Enovid-10, contained substantially elevated dosages, markedly exceeding the considerably lower dosages (0.1–3 mg progestins, 20–50 μg estrogens) characteristic of contemporary contraceptive pills (12).

Despite initial legal and ethical obstacles, prescriptions were permitted solely under the pretext of menstruation regulation until 1969 in nations like Canada. By 1963, Enovid had experienced substantial growth, and was used by approximately 2.3 million women in the United States (12). However, concerns regarding side effects emerged rapidly, particularly the elevated risk of thromboembolism associated with high estrogen doses. These safety issues prompted a gradual reduction in hormonal concentrations and continual improvements in safety profiles over the following decades (13).

The development of the oral contraceptive pill symbolized a broader revolution in medication delivery systems, transcending both social and medical boundaries. A retrospective examination of medication delivery from the 1960s to the 1990s indicates that this era witnessed the emergence of technologies designed for the sustained and controlled distribution of hormones and other pharmaceuticals. These methods aimed to sustain consistent blood and tissue concentration while reducing side effects, establishing a foundation for future modalities such as transdermal patches, subdermal implants, intravaginal rings, and intrauterine systems (12).

Unfortunately, the Dalkon Shield IUD, which was available during that period, was associated with severe pelvic infections and fatalities due to its multifilament tail string that facilitated bacterial ascent from the vagina into the uterus. Although it was withdrawn from the market in 1974, the damage it caused significantly undermined public trust and stalled progress in the IUD field for many years (13).

MODERN CONTRACEPTIVE DEVICES

By the late twentieth century, contraception underwent an evolution characterized by increased options, reduced hormone dosages, and advancements

in drug delivery mechanisms. Legal milestones, such as the 1972 Baird v. Eisenstadt case in the United States, guaranteed access to birth control regardless of marital status, facilitating the diversification of the industry (14). Low-dose hormone pills and copper intrauterine devices (IUDs) were released in the 1980s, indicative signs of scientific progress and a growing social acceptance of family planning. Simultaneously, an increasing number of women decided to pursue jobs in medicine and other fields. Birth control clinics, which were often run by pioneering female doctors like Dr. Marion Powell, who is known as "the mother of birth control in Canada," became more common (12).

During the 1990s, contraceptive innovation moved beyond daily oral administration toward long-acting and user-independent systems. The first contraceptive implant, Norplant, offered long-lasting protection, whilst injectable formulations such as Depo-Provera (Figure 3) further reduced reliance on daily adherence. These developments were made possible by improvements in polymer chemistry, controlled-release kinetics, and biocompatible materials that minimized inflammatory response while maintaining structural integrity. At the same time, the female condom and emergency contraception (Plan B) expanded method diversity and autonomy. By 1995, oral contraceptive use declined to approximately 27% among contraceptive users, partly due to increased condom use amid heightened awareness of HIV and other sexually transmitted infections.

Figure 3. *Depo-Provera injectable contraceptive (medroxyprogesterone acetate) administered via intramuscular injection, illustrating a long-acting, sustained-release hormonal delivery system designed to provide pregnancy prevention for approximately three months per dose (26).*

In the 2000s, biomedical miniaturization and ergonomic refinement became central to contraceptive design. Devices such as the Mirena hormonal IUD, the Implanon rod implant, the Ortho Evra patch, and the NuvaRing vaginal ring exemplified compact, flexible systems engineered for long-term stability within physiological environments. These technologies relied on advanced medical-grade polymers capable of predictable hormone diffusion while remaining mechanically durable and anatomically compatible. User-centered design principles—such as ease of insertion and removal, reduced clinical dependence, minimal visibility, and comfort during daily activity—became integral to development. The second-generation female condom and permanent methods such as Essure similarly reflected iterative design improvements aimed at safety, simplicity, and accessibility (14).

The contraceptive vaginal ring (CVR) represents a significant contemporary breakthrough, serving as a mid-acting, user-controlled contraceptive technique. The combination hormonal NuvaRing which was approved in the Netherlands for use in February of 2001, and in the United States in October of the same year (15), administers etonogestrel (120 μg/day) and ethinylestradiol (15 μg/day) over a three-week period, succeeded by a one-week interval, exhibiting a Pearl Index of 0.25–1.75 pregnancies per 100 woman-years, indicating substantial efficacy and tolerability. Another key development was the progesterone vaginal ring, Progering, launched in Latin America in 2010 (16). Progering dispenses 10 mg of natural progesterone daily and is particularly appropriate for nursing women, prolonging the contraceptive effects of lactational amenorrhea, with pregnancy rates similar to those of IUDs for up to a year of use. These rings have numerous benefits: they are convenient for insertion and removal, available in multiple sizes, and require minimal clinical supervision, making them more accessible (17).

Policy and legislation have also played a critical role in shaping contemporary access to contraceptives. In 2010, the U.S. The Affordable Care Act permitted contraception as preventative care, meaning that insured women no longer had to pay copayments. Later Supreme Court decisions (Burwell v. Hobby Lobby, 2014; Zubik v. Burwell, 2016) allowed religious organizations to omit coverage, underscoring the ongoing tension between reproductive rights and institutional beliefs. Meanwhile, research and regulatory approvals for birth control continued throughout the twenty-first century. In February of 2025, the FDA approved Miudella, a new copper-based, hormone-free IUD that provides long-

lasting, reversible birth control. It adds to established options such as Paragard (approved in 1984) and various hormonal IUDs that are currently in use across the globe (14).

Collectively, these innovations signify a transition towards contraceptive technologies that are safer, more user-center, and tailored to diverse reproductive needs. Modern contraception epitomizes centuries of medical experimentation, ranging from early barrier methods documented in historical texts to contemporary bio-integrated devices, illustrating the ongoing evolution of reproductive health innovations alongside social and scientific advancements.

MALE CONTRACEPTIVE ENGINEERING EFFORTS

Male contraceptives have long faced slow progress in development, with new treatments repeatedly described as being 'five years away' from commercial availability for the past fifty years. The barriers are both structural and biological: whereas women release a single egg per month, men produce millions of sperm daily, making consistent suppression of fertility far more challenging. Beyond biology, limited financial investment has hampered innovation in this field. Pharmaceutical companies have been reluctant to prioritize male contraceptive development, citing anticipated low demand and uncertain market viability (18).

Periodic abstinence, non-vaginal ejaculation, condoms, and vasectomy remain the primary means of male contraception. While both vasectomies and condoms provide reliable protection, only vasectomy is a long-term solution and is not designed to be reversible. This limitation has driven decades of research into alternative approaches, including both hormonal and non-hormonal strategies aimed at expanding male contraceptive options (19).

The most promising male contraceptive techniques have been hormonal, particularly those combining progestin and testosterone. Several studies have shown that these regimens, which are sometimes administered as depot injections, are effective for efficiently and reversibly suppressing sperm production with minimal side effects. A revolutionary male contraceptive gel is currently in advanced clinical trials, building on this foundation. The gel, which contains testosterone and segesterone acetate (Nestorone), is applied to the shoulders daily. Preliminary findings from a multicenter phase 2b trial indicate that 86 percent of males attained contraceptive-level sperm suppression, defined as 1 million or fewer sperm per milliliter, over a median duration of eight weeks, representing a substantial improvement over previous hormonal treatment. Importantly, blood testosterone levels remained within the normal range, facilitating androgen-dependent processes, including sexual function. This study is still assessing safety, long-term efficacy, and reversibility (20).

Non-hormonal methods are becoming available as well. Indian researchers have developed a polymer gel named RISUG (Reversible Inhibition of Sperm Under Guidance), which is injected into the vas deferens while the patient is under local anesthesia. According to research, RISUG, which renders sperm dormant, can give protection for up to thirteen years. While this reversibility has only been demonstrated in animal trials, fertility can be restored with a subsequent injection that dissolves gel. Critics contend that RISUG may act more as a long- term vasectomy alternative than a fully reversible contraception, despite Indian experts' claims about its safety and long-term efficacy (21).

Despite recent advances, male contraception options remain less diverse and accessible than those available to women and current research remains in clinical trials with most data being pre-commercial. The development of long-acting non-hormonal injections and hormonal gels indicates that a reliable, reversible male contraceptive may soon become widely available.

FUTURE CONTRACEPTIVE EFFORTS

In the future, contraceptive methods are expected to become increasingly personalized, accessible, and user-friendly for everyday use. At its core, innovation in this domain is propelled by the principle of equity: ensuring that all individuals, regardless of their location or circumstances, have access to safe, effective, and affordable solutions (22).

Bioinformatics and artificial intelligence (AI) are likely to have a substantial impact on reproductive health in the coming years. Advanced algorithms, trained on vast amounts of data about hormonal cycles, genetic markers, and user feedback, could enable the development of highly tailored birth control regimes with near-perfect precision. This approach would allow individuals to use methods tailored to their unique biology, reducing the need for trial-and-error experimentation, mitigating adverse effects, and enhancing long-term health outcomes. Furthermore, artificial intelligence may be capable of forecasting changes in reproductive health

years ahead of time, serving not only as a contraceptive, but also as a preventive strategy for overall reproductive health (22).

Contraceptive delivery technologies are expected to evolve in ways that go beyond traditional methods. Individuals are likely to begin using microneedle patches, dissolvable implants, and independent bio-integrated devices. Envision a contraceptive chip that interacts with a mobile application, allowing users to easily suspend or resume fertility suppression with a simple software command. While initial prototypes already exist, future iterations may improve user control by automatically adjusting dosages based on real-time biological feedback from wearable sensors (23).

The difference between contraceptive and health technologies is getting progressively less distinct. Multipurpose preventive technologies (MPTs) have the potential to become the norm: single devices or gels capable of not only preventing pregnancy but also protecting against HIV and other STIs, regulate hormones, and provide micronutrients to improve general health. From this perspective, contraception is an essential component of a comprehensive preventive healthcare system rather than a stand-alone intervention (23).

Innovative initiatives are altering the temporal dimensions of contraception with researchers looking into potential solutions that could protect fertility for decades, potentially spanning the period of reproduction. In contrast, current long-acting reversible contraceptives (LARCs) have a limited effectiveness period of months or years (22). Examples of these emerging technologies include biodegradable implants lasting ten years or more, as well as single-injection treatments with reversible effects (23). As a result, reversible male contraception is expected to gain universal acceptance, establishing shared responsibility in family planning as the new standard.

The socio-ethical dimension is equally important, as the next generation of contraceptive technology promotes autonomy, consent, and equity as key principles. Improvements in global health infrastructure, digital telemedicine platforms, and community-led educational programs could ensure that people in low-income countries have access to the most sophisticated reproductive technologies. In this envisioned future, the right to choose the date and location of childbirth is protected by both regulation and technology that is adaptable, unobtrusive, and affordable (22).

The future of contraception will not be determined by a single breakthrough; rather, it will involve a paradigm shift from reactive, standardized techniques to proactive, personalized, and integrated systems that combine biotechnology, digital health, and global equity. In the coming decades, contraception is anticipated to evolve beyond the sole function of preventing conception. It will have a profound impact shaping reproductive autonomy, advancing gender equity, and strengthening long-term global health.

CONCLUSION

The history of contraception is a testament of resilience, innovation, and evolving societal standards. Every step forward, from ancient pessaries and simple barrier devices to modern bio-integrated systems, has expanded new possibilities for reproductive freedom. However, there have also been ethical, health, and political concerns. Contraception is no longer just a way to remain in good health; it is also an essential aspect of women's rights, economic growth, and public health. Looking forward, emerging technologies promise highly personalized, user-controlled, and multipurpose solutions that integrate reproductive care with broader preventive healthcare. The greatest challenge lies in ensuring equitable access so that every individual, regardless of geography or circumstance, can benefit. If realized, the next generation of contraceptive technologies could not only prevent pregnancy but also contribute to making the world healthier, promote gender equality, and restore reproductive freedom as a basic human right.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interests related to this work.

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