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Research Article

Surgical Evaluation of a Full-Body Prosthetic

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Abstract

Background: Rat models were investigated to test the viability of using an artificial body instead of a human one due to the strict immunological, genetic, and physiological criteria.

Case Description: A cylindrical full-body prosthetic fabricated using sterile stereolithography with Accura® 60 was adopted as a test case. The internal organs, spine, and head of a donor rat were transplanted. Due to complications associated with unstable blood flow, the donor animal survived for only 1 hour after surgery.

Conclusions: The findings yielded by this investigation suggested that an improved perfusion system, internal partitions, and insulation would likely improve donor survivability during future attempts of the same procedure. Therefore, our work can assist in the development of technology with the potential to assist terminally ill and severely handicapped individuals.

Keywords: *Full Body Prosthetic, Total Organ Transplant, Artificial Body, Biomaterials, Biomedical Systems Design.*

Introduction

In the existing research, human body analogues were used as an alternative to models for human head transplantation surgery because of the strict immunological, genetic, and physiological criteria required for such procedures [1, 2]. In the present study, a rat model was used to explore the viability of the proposed method. For the purpose of this investigation, the artificial body, or full-body prosthetic (FBP), was designed in the form of a container capable of housing and sustaining the patient's vital organs and maintaining brain function.

The design intention behind the FBP was the provision of all processes and functions essential for life in a single, compact container. In theory, this container could be rendered portable by means of an external chassis controlled by invasive or non-invasive brain–computer interfaces. When this system is proven effective and when its design is streamlined, it would be possible, in theory, to replace failing organs with artificial equivalents, transplanted tissue, or other implants. However, maintaining the optimal conditions for homeostasis remains challenging [1, 2].

Although experiments involving the isolated brain have been conducted for decades, and although many head transplantation attempts have been made, they were unsuccessful. In most cases, tissue rejection, neuronal degeneration, and cerebral ischemia were cited as causes of morbidity [1, 2]. However, in some studies, authors related adverse outcomes to the use of extracorporeal life support systems [3, 4]. To improve surgical outcomes and provide a minimal model for sustaining a transplanted head, as part of the current investigation, a surgical procedure was developed for total organ transplantation in an artificial torso. The development of a viable FBP required material, surgical, and conceptual validation before proceeding to integration of artificial organs and implanted devices.

The FBP is a medical device providing functionality essential for sustaining life and supporting an isolated brain or transplanted head. Isolated brain research was instrumental for the development of cardiac bypass machines and has led to the first primate head transplantation [1]. However, the key limitation of this approach stems from limited postoperative survivability (e.g., 6-8 hours). In a study conducted by White and colleagues, the transplanted head was rejected by the donor's immune system after 9 days [1]. Several authors have attempted to find the solution to the rejection issue and have explored the use of closed-loop combinations of neural tissue and robotics, known as animats and hybrots [5-7].

In several studies, a closed-loop circulatory system was used to sustain a "brain" via homeostatic maintenance of a balance of essential nutrients and waste removal [7-10]. The modular "brains" that were used included a cultured neural network [11], a simulated neural network [7], and a hybrid system using a sealed neuronal culture [6].

Other researchers attempted to utilize the prosthetic body by capitalizing on the very nature of the interface between synthetic materials and organic tissues. For example, empirical evidence suggests that thrombosis could occur due to the mechanical motion of pumping on blood plasma [12,13]. MacLaren and colleagues observed that unwanted clotting could also occur due to biocompatibility issues within the venous material [14]. A comprehensive review of the pertinent literature confirmed that although cultured tissue from the donor may assist in mitigating these issues, the long-term effects of relying on external devices for containing vital organs remain largely

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unexplored.

Authors of existing studies in this field concur that for a transplant to succeed, the synthetic material in contact with the biological tissue must be biocompatible [4,14-16]. The use of an artificial body and different artificial organs, including the heart [17], lungs [18], spleen [19,20], and others [21], has been investigated for decades the reported findings have indicated that the resulting complications are diverse and can include infection [14,15], hemolysis [22], and varying degrees of tissue damage [3,23]. Therefore, in the present study, natural organs were used during preliminary testing.

The FBP is a medical device capable of sustaining life, by means of natural or artificial organs or by providing the minimal required functionality. In the present study, due to the experimental nature of artificial organ technology, transplanted natural organs were used instead. Moreover, rather than implanting organs from one organism to another, entire organ systems were relocated, along with the head.

Although such a surgical procedure has never been performed (to the best of our knowledge), relevant research has been conducted for decades [1]. A review of the pertinent literature revealed numerous attempts at heart and lung transplantations as well as head transplantations in addition to surgeries aimed at mitigating spinal cord injuries and providing artificial life support. Biocompatibility studies of artificial implant materials are also of particular interest.

Transplantations of organs such as the heart, lungs, and kidneys have been performed for decades [1]. However, many of these attempts have not yielded the desired outcomes, mostly due to the short window of viability between the death of the donor and transplantation of the organ into the new recipient, which is typically measured in hours. According to Iyer and colleagues, perfusion of organs in nutrient solutions extended the window in animal model testing [24]. However, sustaining a solitary organ beyond this window has proven elusive.

Isolated brain and head transplant studies have indicated that brain death occurs for a number of reasons. Typically, isolated and perfused brains are sliced for later analysis [1]. In cases aimed at keeping the head or brain alive, similar causes of death have been reported. Findings yielded by head transplant and extracorporeal life support clinical studies indicated that the brain is vulnerable to cerebral ischemia, hemolysis, and sequelae due to mechanical factors [13].

In addition, severing the spinal cord causes gradual atrophy of affected neurons, resulting in severe pain [25]. White and colleagues, after their attempt at head transplantation, reported that they were unable to reconnect the donor head to the spinal cord. The monkey that was subjected to this procedure was effectively paralyzed from the neck down after surgery due to the inability of the severed spine to heal and immune rejection of the donor body [1].

Findings reported in the literature regarding spinal cord injury have indicated that stimulation may be an effective solution to the issue of rejection. Borton and colleagues posited that spinal injuries may be bypassed with implantable electronic devices [26]. According to Gerwig and colleagues, carbon nanotube– based devices resulted in the most significant improvements in biocompatibility [27]. Therefore, electrical stimulation and interfacing with biocompatible electrodes may potentially serve as viable treatment and provide a means of interacting with prosthetics.

The biocompatibility of materials in implantable devices has been extensively studied. Metals, ceramics, polymers, and composites have been used to improve the outcomes of hip implants, which require high strength [28]. Devices in contact with the blood plasma, such as venous stents, can be coated with materials that provide additional strength and elute drugs [15,16,29]. Artificial hearts and blood pumps interface with both interstitial fluid and blood plasma [17,30]. Using the design proposed by the present study, the outer container of the FBP would be in contact with interstitial fluid, materials from artificial cardiac implants, and certain coatings deemed suitable candidates [14,31].

The physiological characteristics of interstitial fluids of the chest cavity vary based on the organs in the closest proximity [21]. Similarly, organs require specific pressures and physiological characteristics to operate effectively [21]. Although these are broad descriptions, heated Ringer's solution for the appropriate animal was used as a stopgap buffer. Materials used to create prototypes of relevant implantable devices and those used in additive manufacturing were used [32].

Materials and Methods

The FBP used in the present study required the design of an entirely novel, life-critical medical device and the development of a surgical procedure. To avoid stress concentrations, a cylindrical body (120 mm in length and 50 mm in diameter) was used, and the device was manufactured using sterile stereolithography with Accura® 60 [21,33]. Although this device was previously used for medical device prototypes, its thermal limitations prevented autoclaving or steam sterilization, thus necessitating chlorine gas sterilization [33].

A number of design aspects were incorporated into the first FBP prototype design. Initially, artificial organs were not investigated; instead, transplanted organ systems were used for simplicity. A small rodent (a rat weighing 100 g) was chosen as an animal model for testing. During this phase, the main considerations pertained to the use of biocompatible material, cost, ease of manufacture, tightness to avoid leaks, durability, and suitable internal volume sufficient for holding the relevant tissue.

A hollow cylinder with a narrow opening on one end was selected for these reasons. This design allowed animal placement; its head protruded from the larger cylinder opening while a catheter could be extended through the smaller hole at the other end for waste removal. In addition, extra skin could be retained near each aperture and sealed tightly against the cylinder with surgical glue. Based on the measurements of an adult white rat, the device was modeled in SolidWorks [34].

The cylinder measured 120 mm in length and its external diameter was 50 mm, with the wall thickness measuring approximately 10 mm. The top (wider) and bottom (narrower) apertures measured 35 mm and 20 mm in diameter, respectively. A "lip" with a thickness of 10 mm was used to provide additional structural support. A total internal volume of approximately 1.26E-1 L was sufficient for a variety of documented rodent body sizes. The amount of Ringer's solution and excess tissue could be adjusted to account for differences in specimen size.

As a part of the present study, five rodent-sized prototypes were fabricated. Each cylinder was made of Accura® 60 [33], a material previously used for implantable device prototypes [32]. The entire batch was assembled using sterile stereolithography at a specialized manufacturing location [35].

Surgical Evaluation of the FBP

The surgical procedure involved transplantation of the cardiopulmonary system, gastrointestinal system, a section of the spine down to the pelvis, and head from the donor's body to the FBP. The aim of the procedure was to evaluate the material biocompatibility, FBP geometry, and viability of the proprietary device.

Placing the tissue into the animal's body required a complex and precise surgical procedure because it was necessary to relocate the essential organs. Specifically, the head, spine, circulatory system, and gastrointestinal system were relocated to the FBP. The aim was to change the internal function of the subject as little as possible to preserve the hormonal and chemical support to the head. In addition, retaining as much of the original structure as possible ensured that the internal organs would be better able to maintain homeostasis within the transplanted tissue.

The FBP was sterilized with chlorine gas prior to surgery. Excess flesh and blood vessels were cauterized to prevent infection and exsanguination. Extra skin near the head and neck was pressed against the aperture in the FBP prior to being sealed with surgical glue. The procedure required implantation of a catheter because the animal would be fed intravenously if damage during surgery rendered the gastrointestinal system unusable.

The catheter was pulled through the bottom, and the subject's head was affixed to the top end. Both ends were sealed with surgical glue, and any excess blood was supplied through the vessels in the animal's neck. Next, measurements of the subject's electroencephalography (EEG), pulse, and other metrics were performed. Although the aforementioned arrangement would preferably last at least 1 week, in the event of premature morbidity, an autopsy was performed to determine the cause of death. Moreover, the artificial body was made partially translucent to observe the organs and ensure that they continued to function.

If any organs required additional pressure to maintain coherent function, then they were bound with sterile gauze. A mechanical respirator was inserted into the mouth to assist with breathing because the diaphragm was cut during surgery. However, in practice, finding an appropriately sized respirator at the exact time of the procedure proved difficult. In this case, alternative arrangements were made.

The thoracic artificial replacement unit for medical applications (TARAUMA) was used during this investigation and required an animal laboratory and surgical finesse. It was used in March 2017, following the review and approval by Harbin Medical University faculty.

Once the animal was anesthetized, TARAUMA involved the removal of the limbs, followed by cauterization of wounds and removal of blood present within them. Incisions on the ventral and dorsal sides of the animal were made and tissue was systematically removed. The spinal column extending to the hips was kept intact. Although ribs were cut away, bones could be broken and left attached if marrow was needed. During the surgery, every precaution was taken to avoid unnecessary damage to the visceral nerves connecting the organs. Then, the viscera were inserted through the top hole of the FBP.

An anesthetized white rat (weighing 100 g) was the primary subject evaluated in the FBP. During surgery, deliberate care was taken to avoid unnecessary damage to the visceral nerves connecting the organs.

Absence of a mechanical respirator necessitated the use of another animal. Therefore, another rat (weighing 350 g) was used to provide constant blood supply and reoxygenation. Organs requiring pressure to maintain coherent function were bound with sterile gauze. A peristaltic pump supplied blood from the donor rat at a flow rate of 10 mL/min.

To maintain body temperature and provide a short-term buffer, the interior of the FBP was filled with pre-heated Ringer's solution. Excess tissue was cauterized to prevent exsanguination. The organs were placed within an opening at the top of the FBP, and the openings were sealed with latex to limit infection vectors. The described process was guided by the premise that the organs would remain viable for as long as nutrients and blood circulation were provided. The organs and the interface between them were evaluated on completion of surgery.

Results

The animal survived for approximately 1 hour after the procedure. The postmortem examination revealed that complications arising from unstable hemodynamics were the primary cause of death. The FBP size necessitated silicone tubes at a high angle, thereby causing complications for the original flow rate of 10 mL/min.

Absence of insulation made it difficult to maintain body temperature. In addition, the body offered no points of attachment to fix the organs in place, resulting in unwanted drift and potential damage. However, no adverse reactions were noted between the body walls and tissues.

Discussion

In addition to the immediate cause of mortality, our findings established that the internal conditions of the body were not suited for sustaining long-term health. The lack of attachment points for the internal organs and insulation rendered organs prone to damage as the body temperature declined. Although this could be mitigated by providing external blood circulation via a pump, this form of life support would not be suitable in the long term. Therefore, we proposed several potential solutions that could be explored in future studies. For example, internal partitions could help address the issues pertaining to the artificial body. Compartmentalization could provide internal stability for vital organ systems, although sealing may still be problematic. Further analysis is also needed to ascertain the long-term effects of exposure to the internal material, although future designs may incorporate multiple layers. To enhance biocompatibility and the immune response, a variety of specific coatings could be used [15].

We also posited that miniaturized blood pumps and respirators could efficiently provide blood reoxygenation. According to Potkay, an artificial lung or artificial support for existing lungs may resolve blood oxygenation issues [18]. In summary, internal integration of extracorporeal perfusion devices, partitioned compartments, and insulation could compensate for the issues encountered in the present study and during prior attempts at similar procedures [4].

For the external device interface, biocompatible electrodes could be invasively implanted along the spine. Alternatively, some combination of non-invasive sensors and stimulation methods to design closedloop systems could be used [7]. In addition, the findings yielded by our investigation could be applied to sustaining patients with terminal diseases and certain types of cancer. They could also assist in designing customizable bioreactors for use in biomedical systems and pharmaceutical research.

Conclusion

The FBP described in this work was designed as a single container capable of holding and sustaining transplanted tissue and required a novel surgical procedure. Despite a highly limited budget, a robust cylindrical FBP with a total internal volume of 1.26E-1 L was designed and implemented. Although testing the long-term biocompatibility of Accura® 60 is still in progress, we have demonstrated that TARAUMA offers a viable method of relocating vital organs in an artificial body. The findings reported here suggest that an improved perfusion system, internal partitions, and insulation would improve donor survivability during future attempts. Therefore, our results contribute to the development of technology with the potential to assist terminally ill and severely handicapped individuals.

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