BME 201 (Biomedical Engineering Design)
Spring 2009

Project #18: Development of a Device for Neurochemical Sample Collection from Freely Moving Monkeys

FINAL REPORT

May 8, 2009

TEAM MEMBERS:
Lauren Eichaker (Team Leader)
Cole Drifka (Team Leader)
Adam Pala (Communicator)
Sarah Springborn (BSAC)
Ben Fleming (BWIG)

CLIENT:
Dr. Ei Terasawa
Department of Pediatrics, UW-Madison

ADVISOR:
Professor Brenda Ogle
Department of Biomedical Engineering, UW-Madison

Table of Contents

Abstract

The goal of this design project is to develop and construct a device to provide protection for the microdrive unit, an apparatus that is used in microdialysis experiments conducted on nonhuman primates. This would allow the experiments to be conducted without restraining the monkeys in a chair, providing them with a more comfortable and realistic experimental setting. Currently, there are no existing devices on the market specifically designed for this purpose. Referring to last semester's prototype, the current design consists of an aluminum casing with a form-fitted silicone rubber interior to surround the microdrive unit. In accordance with the client's requirements, the team is considering alternatives to rework a more lightweight, secure and comfortable device. In the future, the team seeks to implement improvements on factors such as: choice of materials, number of components and overall center of gravity. A different shape and method of cushioning will also be analyzed, with the intent of carrying out further tests on live monkeys. Based on the results of the testing, further modifications will be made.

Problem Motivation

Microdialysis allows for real-time *in vivo* measurements of various substances in the body[2]. In particular, direct measurements of neurochemical substances in the brain from free-moving nonhuman primates is significantly important for understanding complex brain function and developing treatment strategies for brain disorders in humans. A modified microdialysis method has been developed for application to Rhesus macaques (*Macaca mulatta*). However, it requires restraining the monkeys in chairs for up to 12 h while samples are collected. Although this is considered a norm and the monkeys have been appropriately conditioned, the situation is less than ideal since the monkeys are subjected to a certain amount of discomfort due to the restricted movement and long period of chairing. The data collected might also not be representative of a monkey in its natural environment, since it is confined to a chair. One way to address this problem is to allow the monkeys to be free from chairing while the experiments are being conducted. Besides alleviating the discomfort experienced by the monkeys, it would also better simulate the monkey's natural environment since it would be free to move around, albeit within the confines of a cage. Additionally, this method would allow the experiments to be conducted without the 12 h limit imposed by chairing. More time would be available for sample collection and safety inspections to be conducted, allowing the experiments to be carried out more smoothly and safely. However, allowing the monkeys to move freely introduces the risk of them tampering with the experimental apparatus (called a microdrive unit), thus compromising the experimental procedure. Hence, a protective device must be constructed to protect the microdrive unit during the experiment. This device must be compatible with the monkeys such that it will not incur greater discomfort than is necessary or encumber the experimental process. There are currently no products in the market that specifically address this issue, so a suitable device must be designed and constructed.

Background

RHESUS MACAQUE

The Rhesus macaque, also known as the Rhesus monkey, is one of the best known species of Old World monkeys. Rhesus macaques have an extensive geographic distribution and are found ubiquitously throughout mainland Asia, ranging from Afghanistan to India and from Thailand to southern China. They range in color from brown to gray and have little fur, if any, on their reddish-pink faces[5]. On average, adult males measure approximately 53 cm and weigh 7.7 kg. Females are smaller, measuring 47 cm and weighing 5.3 kg on average. Their tails are of medium length, averaging between 20.7 and 22.9 cm, and are not prehensile (i.e. the tails are not adapted to be able to grasp and/or hold objects). Typically, Rhesus macaques have a lifespan of about 25 years[10].

Because of their anatomical and physiological similarity to humans, as well as the relative ease at which they can be maintained and bred in captivity, Rhesus monkeys have long been an ideal choice to carry out research on nonhuman primates. As a result, they have become the most studied nonhuman primate, both in the field and in laboratory settings. Some examples of research involving Rhesus monkeys include the experiments on maternal deprivation carried out by comparative psychologist Harry Harlow in the 1950s, development of rabies, smallpox, and polio vaccines, and the creation of drugs to manage HIV/AIDS[5]. As with all other macaques, the *Herpesvirus simiae* (B virus) is endemic among Rhesus monkeys, but could be deadly if spread to a human. Thus, extra care must be taken when interacting with them.

CLIENT'S RESEARCH

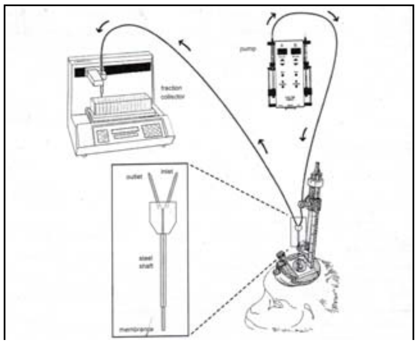


Figure 1. Experimental setup for microdialysis testing

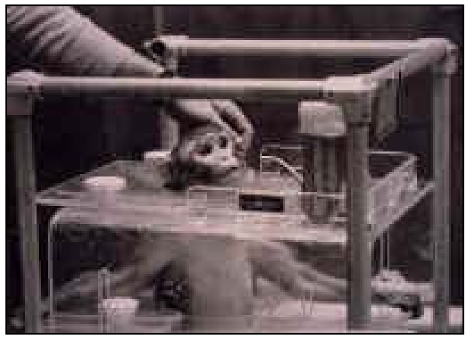


Figure 2. Rhesus Monkey in a Primate Chair[8]

A faculty member at the University of Wisconsin-Madison Department of Pediatrics, the client is interested in understanding how growth and development are controlled in humans. One particular focus is on the role of the brain in triggering puberty[3, 4]. In order to investigate this, the client studies neuroendocrine function by measuring the release of neuropeptides, neurotransmitters, and neuromodulators from the hypothalamus in the brain. Currently, this research is being carried out on Rhesus monkeys, due to their anatomical and physiological closeness to humans. It is hoped that through these neuroendocrine studies on the monkeys, a better understanding of complex brain function in humans can be achieved. Since the studies revolve around the events occurring during puberty, the monkeys used for the experiments are generally young and pubertal. Unlike adult Rhesus monkeys, these monkeys generally range from 2.5 to 5 kg in weight[1].

MICRODIALYSIS & EXPERIMENTAL PROCEDURE

In order to study the release of substances from the hypothalamus of the Rhesus monkeys, a technique known as microdialysis is employed. Microdialysis is widely used in clinical research in areas such as neuroscience (to study the neurochemical bases of brain disorders) and pharmacology (to study drug metabolism, drug delivery, and the effects and efficacy of drugs) [6]. In general, microdialysis entails inserting a probe into the extracellular fluid of a particular part of the body. The probe contains a semipermeable membrane for substances to diffuse in/out based on a concentration gradient. The inlet of the probe is connected via tubing to a pump, which infuses a physiological salt solution. Exchange of substances occurs at the semipermeable membrane, and the desired samples are collected by a fraction collector connected via tubing to the outlet of the probe[2, 9].

A brief outline of the experimental setup used in the client's research is shown in Figure 1. Before experiments can be conducted on the monkeys, a cranial pedestal (head cap) must be implanted into their skulls and secured using dental cement. This allows the microdrive unit to be fitted onto their heads. The purpose of the microdrive unit is to properly position the microdialysis probe for insertion. On the day of the experiment, the monkey is anesthetized and placed in a stereotaxic apparatus. The microdrive unit with a guide cannula are attached and positioned precisely to the specific area desired for testing. Accurate placement is ensured using radiographic visualization. The monkey is then transferred to a primate chair (Figure 2), which it has been conditioned and well adapted to prior to the experiment. Apart from moving its hands to feed itself and turning its head a little, this chair restricts all other movements of the monkey. Once the monkey has been put in place, the guide cannula is removed and the microdialysis probe is inserted. The pump is used to perfuse cerebrospinal fluid (CSF) through the probe and the exchange of substances occurs at the semipermeable membrane (which is in the vicinity of the hypothalamus). The perfusate containing the desired substances that have diffused into the probe are collected by a fraction collector and immediately frozen for storage. The entire experimental process takes approximately 12 h, and the monkeys are confined to the chair throughout this time[1].

Client's Requirements & Design Constraints

The device must be strong enough to provide protection for the microdrive unit such that the monkeys will not be able to tamper with it during the experimental process. This means that the device must be rigid and cover the entire microdrive unit. Taking into account any forces that the monkey may apply, it should also be able to withstand a force of 100 N. This value was an estimate based on human arm strength[7].

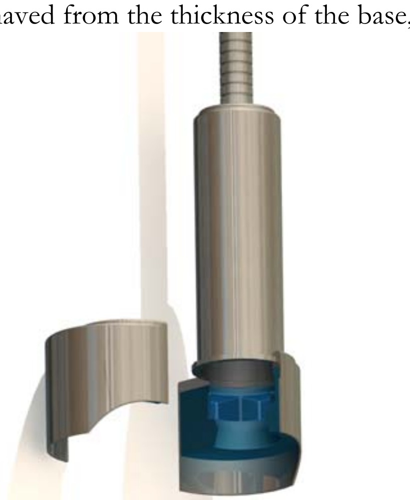
Given that the monkeys are generally smaller in size than the average adult Rhesus monkey, the microdrive unit already imposes a considerable amount of weight on the monkey's head. As such, the materials used to construct the protective device must be lightweight (not more than 0.5 kg, as determined by the client) to minimize the additional weight to be imposed.

The design of the device must be simple such that it can be easily integrated with the current experimental apparatus, so as not to interfere with or impede the data collection process. Yet, a certain degree of complexity must be incorporated to prevent the monkeys from dismantling the device. Also, there must not be any sharp edges or protrusions that can possibly harm the monkey or researcher during the experimental setup and process.

The device should be detachable, so that adjustments to the experimental apparatus can be made during the experiment if needed. This will also allow the device to be cleaned and sterilized prior to subsequent use. In addition, the design and construction of the device must comply with USDA regulations and NIH guidelines, and shall be subjected to approval by the attending veterinarian.

Previous Semester's Design

The previous semester's design of the protective device, now in its third semester, includes several key, distinctive features. The aluminum Cushion-and-Shell Design, originally crafted in the Spring 2008, was modified in the Fall of 2008. Three original aluminum pieces—two base halves and a cylinder—fit together at an interface, thereby protecting the microdrive unit. Modifications include the shortening of the cylindrical top and the drilling of holes into it in order to create a porous aluminum cylinder. Both modifications contributed to a reduction in weight. Excess layers of aluminum were also shaved from the thickness of the base, in an additional effort to reduce the overall weight of the device.



Schematic 1 Last semester's prototype.

A silicone rubber interior secured the device around the head cap and microdrive unit on the monkey's skull. A hose clamp secured the two halves of the base around the silicone rubber interior, and a nylon strap system further secured the apparatus vertically upon the monkey's skull. The tether, which serves as a pathway for sample collection, attached to the cylindrical top via a custom interface.

The previous design (Schematic 1), while a promising prototype, had several flaws that required attention. Despite a considerable reduction in weight (the device currently has a mass of 456.4 g, below the initial client requirement of 500 grams and an 18.9 gram reduction from the first prototype), it is still too heavy for the average monkey specimen; the biggest monkey in the facility could not comfortably undergo experimental observations using this design. Furthermore, the design did not distribute the weight of the device effectively over the monkey's head; the nylon straps appeared to make no appreciable contribution to the stability of the apparatus. All of the weight therefore appeared to be supported by the silicone near the interface; this force then radiated through the aluminum parts and the dental-cement head cap on the monkey. This concentration of the load near the base of the device and at the top of the monkey's head was not ideal for the monkey's well being.

Given the previous design's problems and the client's requirements, the current team needs to implement several modifications. A reduction in weight of the device is of paramount importance and it shall be addressed with precedence over other aspects of the design. Lighter materials shall thus be considered in the design of future prototypes. Notably, the team shall seek a possible replacement for the silicone rubber interior, which currently contributes greatly to the overall weight of the device (the silicone contributes 139.9 grams to the total 456.5 grams). An alternate method of fastening the device also seems necessary (a method which lends itself to more stability, weight distribution, and security). Finally, adjustability of the device must also be taken into further consideration, as the device is intended to accommodate monkeys of various ages and sizes. Resolving these issues likely requires redesigning of the prototype in its entirety, which was the goal of the team at the beginning of this semester.

Redesigned Components

Helmet Component Assessments

The concept of a device that protects the microdialysis unit from the monkeys' tampering efforts centers on a helmet-like piece. Three models are under consideration, rated on their effective weight, ease of construction, safety (from and for the monkey), and ability to withstand force.

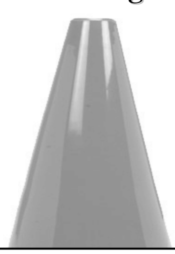
Existing Model Configuration

Available, slightly modifiable and currently too heavy for use, this semester's team has an existing model to reference (see schematic 1). It weighs 475.4 grams (total), has proven durability and the team knows that it fits over a monkey's skull. Silicone rubber used to pad this model seems to be the only viable option, as securing another type of padding inside the cylindrical base proves difficult.

The cons of this model seem to outweigh the pros: the silicone insert used to cushion this model is too heavy for the monkey to support on its own and its center of gravity is easily offset by motion, making the device unwieldy. In addition to these major shortcomings, this model does not fit onto variable monkeys' skulls and there is no obvious way to reduce the weight of any of the existing components. Because this design includes a three-way interface, it also proved difficult to put together by the researchers.

Lastly, the strap system that accompanied this design did not sufficiently secure the device onto the monkey's skull and would need to be reworked.

Conical Design Configuration



Concept 1 A conical design would entail functional straps to stay on a monkey's head.

The conical design consists of a single cone being placed over the microdrive unit and on top of the monkey's head, providing protection for the microdrive unit, but also giving it a little more stability. It utilizes the same concepts as the current design, but addresses the problem of being unwieldy and difficult to put together (Concept 1).

The pros of this model include the fact that, by using a conical design instead of a system of interlocking cylinders, it distributes its mass over the top of the monkey's skull. By incorporating a two-component concept, the conical design would demonstrate a simpler assembly process when compared to the existing model. By making a completely new prototype, this design establishes the option of looking into different materials for its construction and padding. As with the existing model, the team would need to configure a strap system to stabilize this model.

Boxing Helmet Configuration

This configuration would incorporate a helmet portion that would shape nicely to the monkey's head, much like a boxing helmet, coupled with a conical piece on the top of the helmet, meant to protect the microdrive unit and cannula. The entire unit would be one piece and would slide easily down over the monkey's head, spanning from about the monkey's chin to the top of the cannula (Concept 2).

Concept 2 A boxing helmet-like design would be secure in it's coverage of the monkeys' skulls.

This model, which encases the entire monkeys' heads, would distribute the weight of the apparatus evenly and establish a more stable center of gravity compared to the other two models. Its shape addresses the problem of complexity (like the conical design) and would need only a small strap that spans the monkeys' chins to provide extra security.

The cons of this design include the fact that it uses more material to encase the monkeys' heads; this could increase the total weight. It also may be hard to determine the exact dimensions of the monkeys' heads for fitting; padding the unique shape of this conceptual model also poses a problem.

Design Matrix for Helmet Configurations

In order to evaluate the advantages and the disadvantages presented by each model, the team constructed a design matrix. The total weight of the apparatus presents the biggest barrier to construction; 50% of the total points were thus attributed to this factor. This characteristic also assesses the distribution of weight over the monkeys' heads and the effective center of gravity of the device. Upon comparing the three models, the boxing helmet design seemed to satisfy the conditions described and therefore received the highest score in this category.

Ease of construction, while a minimal factor when considering the lifespan of this apparatus and the freedom of movement it would grant the test subjects, designates the viability of a physical prototype. Due to the fact that the previous semester's design, the Cylinder Design, already exists, it received the highest rating in this class. Because of its complexity, the Boxing Helmet design received the lowest score, and the Conical Design, in its simplicity, received the median score.

Equally important, when considering aspects of a new prototype, is the safety of the device for the monkey to bear and the safety it gives to the microdrive unit. Because the Boxing Helmet Design and the Conical Design both distribute their effective weight over the monkey's head better than the Cylinder Design, they tied at a higher mark. Testing would prove which of the two designs, with their tied score, performs better, but the other factors will differentiate one design from the other with respect to which model the team pursues.

The ability of the device to withstand force came under consideration (as in last semester) when considering design alternatives. This factor received the minimum number of points as all of the materials being scrutinized have almost equal abilities to fail under impact; titanium, aluminum metal and hard plastic have all proven themselves able to withstand forces greater than a human or test subject could invoke. Overall, the Boxing Helmet, with its greater area encasing the monkeys' heads ranked the highest. If a force is inflicted on this design, it could distribute the effect over a greater area than the other two designs. The Conical Design, with its evenly distributed center of gravity with respect to the Cylinder Design, thus came in second place; the Cylinder Design loses its balance when the monkey moves about the cage, so the team decided that it deserved last place in this category.

After reviewing these four factors, the design team chose to pursue the Boxing Helmet Design; the Conical Design, which follows closely in second place, may find utilization if the Boxing Helmet Design proves too difficult to construct. A conceptual model will be crafted, and titanium is the current material of choice. Consultation will be taken with specialists to determine alternative choices, however (such as a hard plastic or polymer).

	Weight (50)	Ease of Construction (20)	Safety (20)	Ability to Withstand Force (10)	Total (100)
Boxing Helmet Design	42	15	18	9	84
Conical Design	37	18	18	7	80
Cylinder Design	30	19	16	6	71

Table 1. Design matrix showing the scores for each of the helmet configurations

Strap Component Assessments

The base of the protective device needs to remain securely fit onto the heads of multiple test monkeys. The design from last semester failed to add stability to the protective device. Instead, the aluminum cylinder relied on the interior silicone rubber to remain fixed in place. In order to improve the strap system, the team is considering three distinct applications: one involves using an elastic configuration, one involves using a hard plastic exterior with a foam interior, and one involves refining the current nylon strap configuration.

Elastic Configuration

Concept 3 Elastic could be used to craft customizable straps.

The first option considered involves using a system of elastic straps (Concept 3). It has been proposed to use a material such as Under Armour ® as the baseline material for the straps. The material would be sewn together in a manner so that it could be attached under the subjects' chins. To accommodate various chin sizes, a system of grommets could be inserted into the side of the protective shell. Being able to attach the strap apparatus at different heights relative to the chin may allow for a more specific attachment. Considering the stretch characteristic of Under Armour ®, minor differences in skull conformation (i.e. narrowness, protruded cheekbones) would be accommodated and discomfort should be minimized. The need for incremental adjustments to create a tight fit would be eliminated by the nature of the material.

Ideally, the system should be one component to allow easy use. One disadvantage to the elastic configuration involves making alterations to the material; to attach the ends of the straps to the protective shell on the monkeys' heads, alterations would need to be made. It is currently unknown if sewing or cutting of elastic material would greatly reduce its functionality. If the integrity of the material were weakened by alterations, the monkey's dexterous hands may be able to further damage the apparatus. Another disadvantage may be that the elastic does not "hug" as tightly around the contour of the monkey's face as desired, leading to a reduced degree of security; the monkey might be able to maneuver this design to its mouth.

Hard Plastic with Foam Interior Configuration

The second option makes use of a ratchet idea to fasten a strap system across the protective shell. It has been proposed to fix semi-rigid straps (such as roller blade straps) to the protective shell (Concept 4). The two straps would meet at an interlocking point beneath the monkey's chin. The interlocking mechanism would allow free tightening and prohibit loosening if the monkey tried to alter the connection. Beneath the semi-rigid plastic, soft foam would promote comfort against the monkey's face.

Concept 4 Manipulating hard plastic may lend stability to a strap system.

Difficulty of manufacturing practices is one of the cons of this design. The ratchet component would need permanent attachment to one strap, but remain detachable from the other. The interior foam would need to be attached in a manner so that the monkey could not eventually detach it. Although the semi-rigid plastic would be a very secure option, the increased weight and gaudiness may also be a disadvantage.

Current Nylon Strap Configuration

Concept 5 The concept of a zip tie seems promising, but the nylon straps of last semester did not serve their purpose.

The third option considers improving the current strap apparatus, which makes use of zip ties (also known as cable cords) to fasten two lateral straps to the protective shell (Concept 5). An internally threaded collar zip tie (as opposed to an interface configuration) serves to close that gap. Although the monkey's hands could potentially deform the plastic slightly (using a lot of force), ultimate escape from the apparatus seems unlikely. Once fastened, scissors are required to disengage a zip tie.

This concept is still advantageous when considering adjustability; it is manufactured to fit in very tiny increments (in some cases millimeters). Also, a zip tie's simple design allows for ultimate ease of use by the scientists executing the experiment, and its availability allows for multiple sizes and quantities for use as desired. Simple looping of the nylon to provide for a place to fasten the zip ties presents the easiest option, in terms of construction, on the part of the engineers. A metal loop serves as a position to fasten the nylon to the aluminum base (a rivet secures this loop), and looping of the nylon at its ends works to create a zip tie-metal interface.

The disadvantages of this concept were realized during live testing last semester. One disadvantage associated with zip tie employment involves wastefulness; due to the fact that it takes three zip ties to secure the straps and that they only function for one use, their use involves wasting material and requires subsequent re-purchasing by the lab staff. Also, the shape of the apparatus did not adequately "hug" the head of the monkey. Furthermore, there was a concern that the lateral straps may put undesirable pressure on the facial nerves of the monkey. To improve this, it was proposed to change the shape of the apparatus to possibly run along the back of the head. Also, alternative materials to nylon, such as soft leather, may reduce concerns pertaining to the facial nerves.

Design Matrix for Strap Configurations

In order to evaluate the three alternatives for the strap design, a separate design matrix was created with different weighted criteria and the designs were ranked in each category. Security from monkey is a very important criterion for the design; the method of fastening the straps must be secure and complex enough such that the monkey would not be able to dismantle it. If the monkey is able to figure out how to undo the straps, it would greatly compromise the stability of the entire device. The hard plastic design would be the most secure, since it requires a release mechanism to undo the straps. Hence, the monkey would not be able to undo the straps, as the release mechanism is protected. The zip tie design is also secure, since it is virtually impossible to undo a locked zip tie without the use of scissors. The elastic design is the least secure, since the monkey might readjust where the straps fall on the face.

An equally important criterion is the adjustability of the strap design; the straps must be adjustable so that they can fit monkeys of different head shapes and sizes. The elastic design would be the most adjustable since the material is virtually continuous in its ability to stretch. The current zip-tie design depends slightly on incremental adjustments. However, the existence of three adjustment sites (two laterals, one collar) makes this design more adjustable than the hard plastic design, which has one adjustment point.

The strap design must also be easy to use by the experimenters, so that time will not be sacrificed trying to figure out how to secure the straps. The elastic design, if sewn into a configuration that allowed for a single temporary attachment point, would be the easiest to attach. The hard plastic strap design seems to present the most difficult procedure for assembly, while the current zip tie design seems straightforward and simple. The zip tie concept only involves looping the zip tie around the straps and pulling to fasten it. However, three attachments may be more cumbersome than the one attachment in the hard plastic design.

The last criterion is the ease of construction. Similar to the cylindrical top, the chosen strap design must be relatively easy to construct so that it can be used by the client and possibly reproduced. The elastic design would be the most reproducible and easiest to construct, since only elastic material and an attachment piece is being proposed. On the other hand, both the hard plastic and nylon designs may be more difficult to construct because both require combining adjustable components with comfortable strap material.

	Security from Monkey (40)	Ease of Use (15)	Adjustability/Comfort (30)	Ease of Construction (15)	Total (100)
Elastic – No Clasp	27	14	22	14	77
Hard Plastic with Foam	36	10	22	12	80
Nylon Reconfiguration	32	12	10	10	64

Table 2. Design matrix showing the scores for all of the strap configurations.

Padding Component Assessments

The helmet configuration that the team has developed needs to fit snugly onto multiple monkeys' heads. The helmet thus requires some sort of padding which is flexible enough to handle a relatively wide range of monkey head sizes while at the same time keeping the helmet stationary and secure to the monkey's head. The padding must also be sufficiently comfortable and lightweight.

Memory Foam Configuration

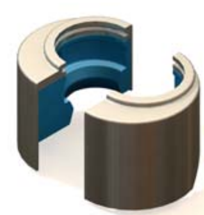
Concept 6 Memory foam comes in variable densities and is disposable; these are qualities the team seeks in a padding option.

Pieces of memory foam, cut to fit the shape of the helmet, could be used to cushion the interior of this apparatus (Concept 6).

Although memory foam appears highly customizable, it would take time for the lab personnel to craft new layers of padding for each monkey each time they wished to carry out an experiment. This one-time-use quality could prove expensive and wasteful, as there is no way to sterilize memory foam. Monkeys could also pick memory foam apart during the experiment; the monkeys can safely ingest this material, but this act is undesirable by the lab staff.

Overall, memory foam seems easiest to purchase and replace, but poses many issues upon closer inspection.

Silicone Configuration



Concept 7 With its known properties, silicone rubber is a promising option.

Last semester's team involved a silicone rubber insert (Concept 7) meant for their cylindrical design; with adaptation, this could fit with the current design team's concept. The porous silicone rubber padding held the microdrive unit in place during testing, while sufficiently cushioning the monkey's skull. Its known performance and properties during testing and ability to be sterilized are its only pros however.

Silicone rubber, by nature, is very heavy and accounts for most of the weight of the current model. Unable to contour to varying monkeys' head sizes, this material proves the least adjustable of the team's options. The high price of the material and relatively difficult manufacturing practices associated with its molding also add to the disadvantages associated with the existing idea.

Silicone and Memory Foam Combination

One possible solution involves combining silicone and memory foam for the padding. Pieces of memory of foam would be used to line the helmet to provide cushioning and support. The foam could utilize Velcro or snap fasteners to attach to the interior of the helmet. The porous silicone would be molded to fit around the microdrive unit to protect and provide support, as in last semester's design.

The positive aspects of memory foam are that it is easy to obtain, easy to craft and would be fairly comfortable for the monkey. The positive aspects of porous silicone are that it provides considerable strength and security to the apparatus. In the previous semester's design, the silicone provided nearly all of the stability needed to keep the device attached to the monkey's head.

The downside of memory foam, as mentioned above, is that it does not appear to be flexible enough with respect to sizing for different primate subjects. Also, this option might prove costly and unsafe to the monkeys; when all of the forces act on their head caps, detachment of the dental cement from their skulls could occur. The main disadvantage of silicone is that it is heavy, and the extra weight puts considerable strain on the monkey's neck.

In summary, a combination of memory foam and porous silicone for the padding would likely be the most secure option. However, it would also be the most expensive and heavy choice. This design does not allow for a wide range of monkey skull sizes, so the cons seem to outweigh the pros for this particular alternative.

Inflatable Bladder Configuration

Concept 8 A bicycle pump would be used to inflate/deflate the air bladder for a custom fit.

The team has come up with the idea of lining the inside of the helmet with an inflatable air bladder composed of thin, flexible plastic. The two-pieced design will snap into the helmet via snap fasteners. Each air bladder will have a valve for inflation, which will be accessible through an opening in the back of the helmet.

Advantages of this design include the fact that the air bladder will provide a wide range of sizing for different monkey heads, and be sufficiently lightweight. The bladder should be relatively cheap and easy to manufacture, while still providing sufficient stability to the helmet. The air bladder configuration will be able to be sterilized and thus re-useable. Lastly, it should take a small amount of time to inflate the air bladder to the correct amount, thus increasing the ease with which the entire device is placed on the monkey's head (Concept 8).

Some disadvantages of this design include the inability of the bladder to wick away any perspiration from the monkey's head. Also, if the monkey can gain access to the air bladder, it may be able to deflate it (if the bladder is not sufficiently thick). Furthermore, the plastic of the air bladder may also be uncomfortable and/or abrasive to the monkey's head. There are a few possible solutions for the flaws of this design. The monkey could wear a headpiece underneath the helmet made of Under Armour ®, or similar material. The air bladder and helmet could also have corresponding holes in their design (those in the air bladder would be sealed of course, so as to present air escape). These two solutions could aid in keeping perspiration from accumulating on the monkey's head, as well as taking care of the abrasive nature of the plastic. Also, the inner surface of the bladder could have a micro fiber coating to increase comfort.

Design Matrix for Padding Configurations

Security from monkey arises as the most important factor when analyzing materials used to pad this apparatus; it received 40% weight in the comparison of methods. In the event that the monkey obtains a piece of or ingests the material used, this material must not harm the monkey. The material of choice would be either reusable or very cheap/easy to reconstruct if disposable. An ideal solution would provide utmost adjustability for the lab staff and allow a comfortable experience to the monkey. Ease of construction by the team was also considered. Memory foam and silicone tied for second place, their differences offset by their varying qualities. A combination of the two materials however, poses the problem of how to interface the two materials, so it remains in last place on the design matrix, despite its current existence and known qualities. An inflatable air bladder concept seems the most viable of the options considered. Upon investigation, it would be the easiest to assemble by the lab staff, the most adjustable and also the most comfortable for the monkey; if the material is chosen correctly, it would be able to withstand tampering by the test subject. The inflatable air bladder hence received the highest score and the team is investigating methods of construction.

	Safety from Monkey (40)	Ease of Use (15)	Adjustability/Comfort (30)	Ease of Construction (15)	Total (100)
Memory Foam	27	13	28	14	82
Silicone	35	8	15	14	72
Combination (Memory Foam and Silicone)	30	9	19	12	70
Inflatable Bladder	31	14	26	13	84

Table 3. Design matrix showing the scores for the padding configurations.

Final Design

Figure 3 The silicone rubber insert, microdrive unit, watchstrap and outer shell from the prototype.

The final design is a combination of each of the top rated components in each design matrix (Figure 3). This design is composed of a hard plastic helmet, molded via positive mould thermoforming that fits snugly around a small ring of silicone that interfaces directly with the microdrive unit. The silicone piece provides stability and cushioning for the microdrive unit and also ensures that the helmet is placed correctly on the monkey's head. The silicone is molded to fit precisely inside the helmet, guaranteeing that the entire helmet does not tilt and accidently touch the cannula. The plastic rests directly on the silicone, so it also prevents the helmet from putting any direct pressure on the top of the monkey's head. The silicone is cut in half vertically so that it can be placed securely around the microdrive unit before the helmet is placed on the head (Figure 4).

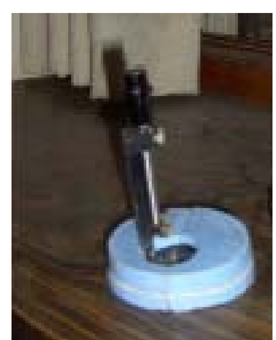


Figure 4 The silicone rubber fits tightly around the microdrive unit.

The shape of the helmet consists of a cylindrical base going around the monkey's head and a cone that is tilted forward so the apex of the cone is directly above the forehead of the monkey (see appendix II). The cone is tilted forward to ensure that it does not interfere with the cannula that is located close to the monkey's forehead and perpendicular to the top of the head. A section of the cylinder is cut out for the monkey's face and ear holes are cut out for the monkey's comfort. There is also a small hole cut out of the top of the cone, intended to interface with the tether that protects the microdialysis tubing. The entire helmet is one piece and slides down over the monkey's head.

The helmet itself is made of one layer of high-density polystyrene. Initially, the design called for two layers of plastic, with a thin layer of foam in between them, but after some initial, human-induced force testing, the plastic proved to be very strong and sturdy at this thickness and would be able to withstand any force the monkey could produce. The plastic was heated to a pliable consistency and then placed over a positive mould in a process called thermoforming (Appendix III). The mould is made of wood and is the shape of the inside of the helmet. When the plastic is placed over this mold, a vacuum helps to pull the pliable plastic over the mould to form the desired shape. The plastic is then cooled to room temperature and the edges trimmed into the final shape. Two separate pieces plastic were made (one for each side of the helmet, cut vertically) and then glued together at the edges. The plastic provides enough stiffness and durability to protect the microdrive unit without the weight of metal.

Figure 5 The inflatable air bladder cushions the monkeys' skulls and keeps the helmet securely on their heads.

To provide cushioning for the monkey's head while the helmet is in place, a custom air bladder was added to the design (Figure 5). This air bladder is located below the dental cap and does not directly contact any of the microdialysis equipment. It wraps around behind the monkey's head, providing a downward force to hold the helmet in place. It can be inflated to the tension that best fits the monkey being tested, providing the needed security and eliminating a great deal of discomfort. This also allows the device to be used on a variety of head sizes. The air bladder is also recessed into the helmet a little as to eliminate a great deal of picking and poking from the monkey. A small leather watchstrap is attached to the corner of the helmet near the face. This chinstrap is an extra precaution so that the monkey will not be able to remove the helmet. It also ensures that the helmet is snug on the monkey's head and will not slide around during movement.

Human Factors and Ergonomics

Taking into account the human and animal factors active during the use of the prototype, the design team plans to: include safety features to protect the human and animal from harm, provide a descriptive schematic for assembly of the final apparatus in the lab, provide a final weight of the product and include a list of the product's limitations.

All dangers related to this device come from mechanical actions; no sharp edges are incorporated into the design for this reason. As this apparatus has few moving parts, it provides a wide margin of error for the scientists putting it together; thus, the test subject would not be harmed if this device were put together incorrectly, but the results of the experiment may prove void. By incorporating a design centered around one main piece placed snuggly on a silicone ring, the team sought to essentially eliminate the physical effort and time necessary to assemble the pieces in the lab, thereby significantly reducing the amount of error that may occur.

The chosen outer material was proven to hold against forces beyond the capabilities of the test subject and most humans, while the chosen inner materials were selected to provide comfort and cushioning for the test subject's head. High-density polystyrene was selected for the helmet construction because it has the sturdiness needed to prevent any bumping of the cannula or microdrive unit, which could cause significant harm to the test subject. The air bladder was created from a soft rubber that will not be abrasive to the test subject's head and will provide the necessary inflation to keep the helmet stable on the head. Finally, the silicone ring, to be placed around the microdrive unit, will be formed to shape of the helmet. This guarantees that the device is centered on the monkey's head, thereby reducing the possibility that the helmet will interfere with the cannula. Overall, once in place, there should be little to no movement of the helmet, for the safety of the monkeys.

There will be a step-by-step protocol written up, in collaboration with the primate lab, to ensure that the device is implemented correctly on the monkey's head. This will be edited and approved by Dr. Terasawa's lab and various veterinarians that work with the monkeys in question. This should reduce the chance of an improperly-positioned device.

Testing

Picture 1 Testing was carried out using a force scale.

Several quantitative tests were carried out to ensure the stability of the prototype on a monkey mannequin prior to its installment on a live candidate. First, over 20 N of force was applied to a force scale (picture 1) attached to the interior of the helmet, simulating a monkey's attempt to pry the helmet off (the head of the monkey was held down by a team member). Next, the helmet sustained forces of up to 12 N in the side-to-side and front to back directions; consistently staying on the mannequin, the amount of force the team applied was limited by the signs of decapitation from the base that the mannequin displayed.

WEIGHT OF PROTOTYPE

The current weight of this prototype is 134.1 grams with the inflatable airbladder, and watchstrap, but without the silicone insert bladder; the silicone rubber insert adds 131.8 grams to the overall weight. The total weight of the prototype (once fully assembled) is thus 265.9 grams. This weight is good for the monkey and a significant reduction from last semester's prototype (475.4 grams). The low weight of the outer shell allows for more weight to be inserted elsewhere in the design in case of the need for added stability or comfort. The primate house will carry out qualitative tests at a later date; these will test the ease of assembly by individuals not in the engineering field and under time constraint on a live monkey.

Conclusions

After carrying out testing on the prototype, the team concludes that it is safe to test the device on a live subject. There will be no way for the monkey to disassemble the helmet once it is installed, due to the fact that we created a single-piece prototype; for example, the chinstrap may only be disengaged using scissors or a blade. The UW Primate house will verify these quantitative tests by qualitatively evaluating the performance of the device on a rhesus monkey with veterinary supervision. Any alterations needed by the primate house with respect to the sizing of the helmet may be achieved by creating a variably sized mould and subsequent thermoforming of another shell. The team thus concludes that the practices utilized, and the schematic referred to in order to achieve this prototype, should serve as a major part of the solution to the problem of allowing a primate to move freely during microdialysis testing.

Future Work

The current plastic prototype lacks any attention to the metal tether that attaches to the top of the helmet. In the past, this has contributed a great deal of the weight that the monkey's head and neck must sustain. One possibility to alleviate a majority of the weight felt by the monkey is to incorporate a dual swivel system into the design. This system, which has already been developed for use in rat microdialysis experiments, could be scaled up to a size appropriate for use with monkeys. The design incorporates two separate joints that would allow the monkey a great deal of freedom to move around its cage, while still supporting the majority of the weight.

Once the initial prototype has been completed and tested, if it proves to be very effective, the client would like to consider the possibility of producing a second, smaller helmet. While the design is intended to be adjustable to fit a variety of head sizes, it would be much more effective to have a smaller helmet for the younger monkeys. Minimizing the amount of excess air space between the monkey's head and the helmet is also necessary, as it would provide a greater deal of stability. This is essential because slight movement of either the microdrive unit and/or microdialysis probe could cause experimental error in data collection or even result in injury to the monkey. Thus, producing helmets of slightly different sizes will be much safer and more comfortable for the monkeys[1].

[1] Our concept solves this issue, but would need more attention to the calculation of exact dimensions for the different moulds necessary to craft variable helmet sizes.

A customized, inflatable air bladder would also improve upon this prototype. The current model, fashioned from a bicycle tire, puckers due to the curvature of the helmet; a custom molded airbladder would have dimensions to alleviate this issue.

Hopefully, once the necessary improvements have been made, the device will be suitable for use by the researchers to improve the microdialysis experimental procedure, and create a more comfortable and natural environment for the monkeys.

Ethical Considerations

Since this project involves creating a device for monkeys used in research, there are some ethical issues surrounding the project. Prior to embarking on this project, the team has been assured that all research carried out with these animals follows all governmental regulations and that the animals are treated in a humane manner. There are limitations placed on the amount of experimentation that can be carried out with the monkeys and they are under the constant care of the Wisconsin National Primate Center veterinarians. The goal of this project is to construct a device that ultimately allows the monkeys to be more comfortable and natural while research is being conducted. Hopefully this will improve their quality of life. In addition, when creating the device, the team kept the comfort of the monkey in mind. The team tried to design a device that would be as light and comfortable as possible, while still providing the necessary protection. Throughout this process, there has been constant contact with the veterinarians to ensure that the device satisfies all safety requirements and will impact the monkeys in a positive manner.

References

1. Frost, S. I., Keen, K. L., Levine, J. E., and Terasawa, E. 2008. Microdialysis methods for *in vivo* neuropeptide measurement in the Stalk-median eminence in the Rhesus monkey. *J Neurosci Methods*. **168** (1): 26-34.
2. Müller, M. 2002. Science, medicine, and the future: Microdialysis. *BMJ*. **324**: 588-91.
3. Terasawa, E. 2006. Postnatal remodeling of gonadotropin-releasing hormone I neurons: toward understanding the mechanism of the onset of puberty. *Endocrinology*. **147** (8): 3650-51.
4. Terasawa, E. 2005. Role of GABA in the mechanism of the onset of puberty in non-human primates. *Int Rev Neurobiol*. **71**: 113-29
5. Cawthon Lang, K. A. 2005. Primate Factsheets: Rhesus macaque (*Macaca mulatta*) Taxonomy, Morphology, & Ecology [Online] pin.primate.wisc.edu/factsheets/entry/rhesus_macaque
6. Ekstrøm, P. O. 2006. Microdialysis [Online] www.radium.no/srg/?k=srg/Microdialysis&aid=5401&submenu=5/
7. The EAP/Human Armwrestling Match. 2008. [Online] ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-armwerestling.htm
8. The Mary T. and Frank L. Hoffman Family Foundation. 2008. S. A. E. N. [Online] all-creatures.org/saen/res-fr.html
9. Wikipedia. 2007. Microdialysis [Online] en.wikipedia.org/wiki/Microdialysis
10. Wikipedia. 2008. Rhesus Macaque [Online] en.wikipedia.org/wiki/Rhesus_Macaque
11. McMaster-Carr. 2008. More About Aluminum and Aluminum Alloys[Online] www.mcmaster.com
12. K-mac Plastics. 2008. HDPE (High Density Polyethylene) Typical Properties [Online] www.k-mac-plastics.net/data sheets/hdpe.htm

APPENDIX I: PRODUCT DESIGN SPECIFICATIONS

PROJECT TITLE:

Development of a Device for Neurochemical Sample Collection from Freely Moving Monkeys
(Project Number: 18 / Project Code: neurochemical_sampling)

INITIAL PROBLEM STATEMENT:

The purpose of the project is to develop a device allowing monkeys to be free from chairing while experiments are conducted. Direct measurements of neurochemical substances in the brain from free moving non-human primates is significantly important for understanding complex brain function and developing treatment strategies for brain disorders in humans. During the past semesters, BME students designed and built devices. However, this device still needs further refinement for actual application. The development of the device for microdialysis experiments will require creativity, intellectual exercise and ergonomic expertise.

REVISED PROBLEM STATEMENT:

To improve on the device created last semester that protects the microdialysis apparatus used during cranial experiments on non-human primates. This involves continued efforts to reduce the weight of the device, secure it around the monkey's head, and better able to cushion the microdrive unit.

CLIENT REQUIREMENTS:

- Material must be effectively lightweight so as not to impose too much weight on the monkey's head.
- Material must be strong enough to withstand forces that the monkey may apply.
- The device must not interfere with the data collection process.
- The device must be able to be easily integrated with the current microdialysis apparatus being used.
- The monkey must be able to move freely with the device attached to it.
- There should be limited space between the device and the microdialysis apparatus.
- The device must be detachable from the apparatus after use.
- The device should be sterile and reusable.

DESIGN REQUIREMENTS:

1. Physical & Operational Characteristics

a. **Performance Requirements:** The device must be strong enough to withstand 100 N (based on human arm strength estimate) to protect the microdrive unit from any forces that the monkey may apply.

b. **Safety:** The device must not contain sharp edges or other protrusions that may injure the monkey or researcher. The materials that are used must not be toxic.

c. **Accuracy & Reliability:** The device must provide reliable protection for the microdrive unit by being able to withstand a force of 100 N for 10 consecutive hits within a time period of 10 s.

d. **Life in Service:** The device must be able to withstand at least 12 hours of use at a time, and must be sterile so that it can be reused.

e. **Shelf Life:** At least 5 years.

f. **Operating Environment:** Normal laboratory environment for non-human primate research.

g. **Ergonomics:** The device must not restrict the monkey's motion except for the head and neck.

h. **Size:** The base of the device should have a diameter of 3 1/4 in and a maximum height of 2 7/8 in (height differs due to the shaping of the base to provide a custom fit for the Rhesus monkey's head). The upper cylinder should have a diameter of 2 in (with a 1/8 in lip around the bottom) and a height of 6 in.

i. **Weight:** Not more than 0.5 kg so as not to impose too much weight on the monkey's head (as determined by client). Tests conducted last semester proved the original 0.5 kg maximum weight too high; the effective weight of the apparatus must be reduced.

j. **Materials:** Aluminum alloy 5052 for the outer casing and soft foam for the form-fitted interior. Current materials are subject to review; titanium and tough plastics are under review.

k. **Aesthetics, Appearance & Finish:** The device must be aesthetically pleasing and look "humane" so as not to create a public outcry.

2. Production Characteristics

a. **Quantity:** 1 reproducible device.

b. **Target Product Cost:** Not more than USD1000.

3. Miscellaneous

a. **Standards & Specifications:** The design and construction of the device must comply with USDA regulations and NIH guidelines, subject to approval from the attending veterinarian.

b. **Customers:** Primarily the client, but can be potentially extended to any research institution that is involved with cranial microdialysis studies on non-human primates.

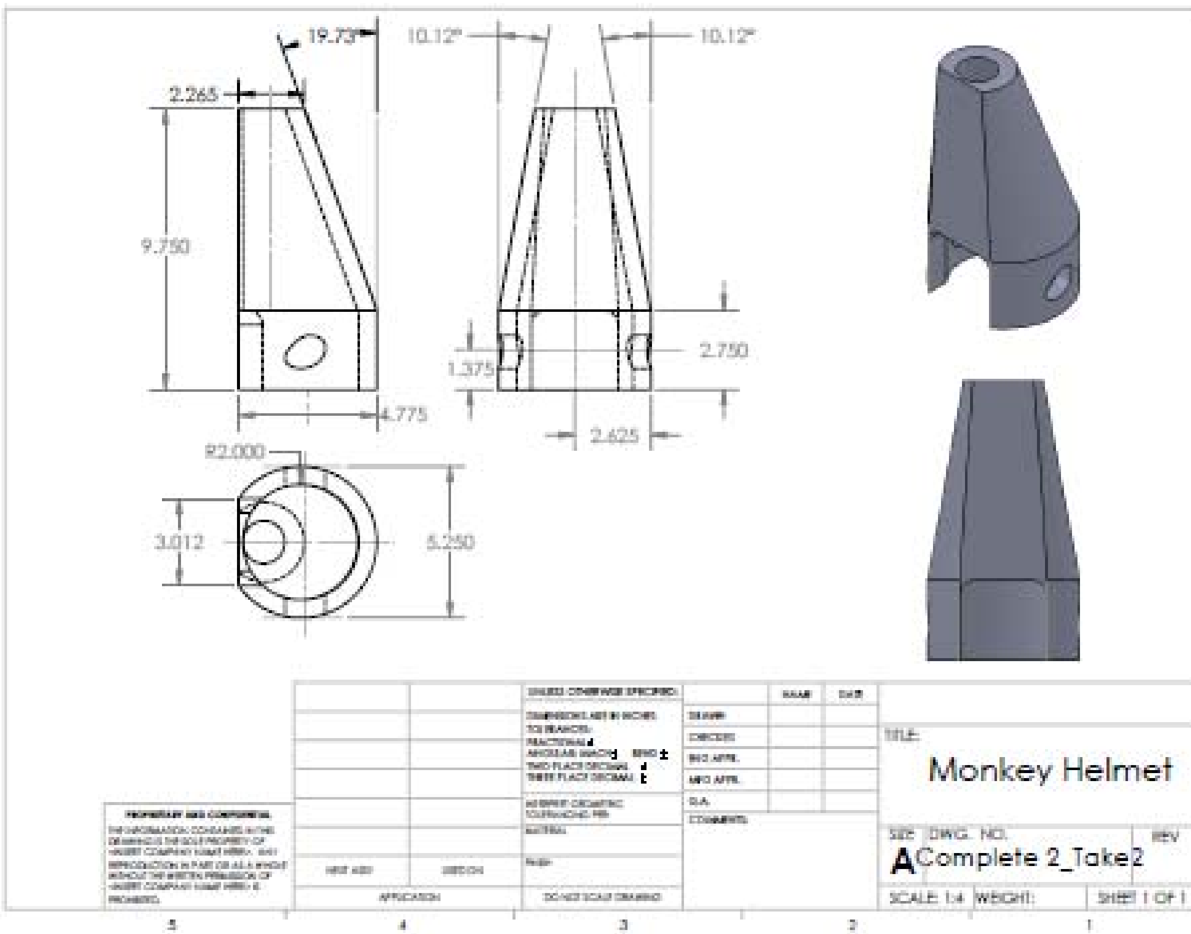
c. **Patient-Related Concerns:** The device must be sterilized before use with a different primate. It should not cause more discomfort to the monkey than the current experimental apparatus (i.e. the primate chair).

d. **Competition:** No currently known products specifically address the need to protect the microdrive unit during cranial microdialysis studies on non-human primates.

APPENDIX II: PROJECT EXPENDITURE

ACE Hardwear Superstore.com#1241199, Manf#: P74300125-V, Foam Board Adhesive, 10.2 oz : $4.49
2 - McMaster Carr Supply Co#8595K77, 1 lb Kit RTV Silicone Casing Compound $39.08
McMaster Carr Supply Co#7636t31, smooth rod caulk gun: $5.68
Watchpartusa.com LEA309-20SS, Watch Band, Leather, Heavy 20mm, Black: $12.95
Total: $101.28

APPENDIX III: SOLIDWORKS Drawing



Appendix III: Thermoformer Pictures

Picture 2 The moulds in place on the thermoforming machine.

Picture 1 Looking downwards into the thermoforming machine.