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Application of IT in Nanorobotic

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Abstract : *This paper will describe a micro/nano scale medical robot that is within the range of current engineering technology. It is intended for the treatment and/or elimination of medical problems where accumulation of undesired organic substances interferes with normal bodily function, such as:*

- *Tumors*
- *Arteriosclerosis*
- *Blood clots leading to stroke*
- *Accumulation of scar tissue*
- *Localized pockets of infection*
- *Others*

While much speculation has been published on possible far-future applications of nanotechnology using advanced materials and manufacturing techniques, relatively little has been published on applying existing engineering technology to the problems in order to create a solution that can be incrementally improved as the technology becomes available. In this paper, we will describe a mobile robot that can be created with existing technology, that can be used to seek out and destroy inimical tissue within the human body that cannot be accessed by other means.

The construction and use of such devices would result in a number of benefits. Not only would it provide either cures or at least a means of controlling or reducing the effects of a number of ailments, but it will also provide valuable empirical data for the improvement and further development of such machines. Practical data garnered from such operations at the microscopic level will allow the elimination of a number of false trails and point the way to more effective methods of dealing with the problems inherent in operation at that level.

We will address and propose solutions to problems such as size, method of entry into the body, means of propulsion, means of maintaining a fixed position while operating, control of the device, power source, means of locating substances to be eliminated, mans of doing the elimination and how to remove the device from the body afterward. During the course of this we will also discuss the appropriate manufacturing techniques for the construction of the device.

Key Words : *Nanotechnology, X-Ray, Infection, Arteriosclerosis, Propeller, Cilia/flagellae*

1. Introduction

This paper will deal with the problems involved in designing and building a micro-scale robot that can be introduced into the body to perform various medical activities. The preliminary design is intended for the following specific applications:

1.1. Tumors. We must be able to treat tumors; that is to say, cells grouped in a clumped mass. While the technique may eventually be used to treat small numbers of cells in the bloodstream, this is normally done effectively by white blood cells and antibodies, and this technique is not intended to replace that. The specified goal is to be able to destroy tumorous tissue in such a way as to minimize the risk of causing or allowing a recurrence of the growth in the body. The technique is intended to be able to treat tumors that cannot be accessed via conventional surgery, such as deep brain tumors. However, since the technique is extremely effective and much less debilitating than conventional surgery, it should be used, if possible, as a replacement for conventional surgery in this application.

1.2. **Arteriosclerosis**. This is caused by fatty deposits on the walls of arteries. The device should be able to remove these deposits from the artery walls. This will allow for both improving the flexibility of the walls of the arteries and improving the blood flow through them. In view of the years it takes to accumulate these deposits, simply removing them from the artery walls and leaving them in the bloodstream should allow the body's natural processes to remove the overwhelming preponderance of material.

1.3. **Blood clots.** The cause damage when they travel to the bloodstream to a point where they can block the flow of blood to a vital area of the body. This can result in damage to vital organs in very short order. In many if not most cases, these blood clots are only detected when they cause a blockage and damage the organ in question, often but not always the brain. By using a microrobot in the body to break up such clots into smaller pieces before they have a chance to break free and move on their own, the chances of ensuing damage are reduced greatly.

We must consider the following factors when designing our microrobot:

- How do we introduce the device into the body?
- How do we move the device around the body?
- How do we know where the device should go?
- How do we control the device?
- How is the device powered?
- What does the device do when it gets there?
- How do we remove the device when its job is done?
- How do we introduce the device into the body?

We need to find a way of introducing the nanomachine into the body, and allowing it access to the operations site without causing too much ancillary damage. We have already made the decision to gain access via the circulatory system, which leaves us with a number of considerations.

The first is that the size of the nanomachine determines the minimum size of the blood vessel that it can traverse. Not only do we want to avoid damaging the walls of whatever blood vessel the device is in, we also do not want to block it too much, which would either cause a clot to form, or just slow or stop the blood flow, precipitating the problem we want to cure in the first place. What this means, of course, is that the smaller the nanomachine the better. However, this must be balanced against the fact that the larger the nanomachine the more versatile and effective it can be. This is especially important in light of the fact that external control problems become much more difficult if we are trying to use multiple machines, even if they don't get in each other's way.

The second consideration is an even simpler one; we have to get it into the body without being too destructive in the first place. This requires that we gain access to a large diameter artery that can be traversed easily to gain access to most areas of the body in minimal time. The obvious candidate is the femoral artery in the leg. This is in fact the normal access point to the circulatory system for operations that require access to the bloodstream for catheters, dye injections, etc., so it will suit our purposes nicely.

2. How do we move the device around the body?

One of the first problems to solve is how to get our device to the problem area in the first place. We start with a basic assumption: we will use the circulatory system to allow our device to move about. We must then consider two possibilities: should it be carried to the site of operations, or should it be propelled? We will start by dismissing the idea of using a probe, catheter or umbilicus to move the device around since this would be very difficult to make versatile enough.

The first possibility is to allow the device to be carried to the site of operations by means of normal blood flow. There are a number of requirements for this method to be practical. We must be able to navigate the bloodstream; to be able to guide the device so as to make use of the blood flow. This also requires that there be an uninterrupted blood flow to the site of operations. In the case of tumors, there is very often damage to the circulatory system that would prevent our device from passively navigating to the site. In the case of blood clots, of course, the flow of blood is dammed and thus our device would not be carried to the site without the capability for active movement. Another problem with this method is that it would be difficult to remain at the site without some means of maintaining position, either by means of an anchoring technique, or by actively moving against the current. While the above objections do not eliminate any possibility of ! using this technique, they do point out the need for at least a supplementary means of locomotion.

2.1. Propeller

The very first Feynman prize in Nanotechnology was awarded to William McLellan for building an electric motor that fit within a cube 1/64th of an inch on a side. This is probably smaller than we would need for our preliminary microrobot. One or several of these motors could be used to power propellers that would push (or pull) the microrobot through the bloodstream. We would want to use a shrouded blade design so as to avoid damage to the surrounding tissues (and to the propellers) during the inevitable collisions

2.2. Cilia/flagellae

In this scenario, we are using some sort of vibrating cilia (similar to those of a paramecium) to propel the device. A variation of this method would be to use a fin-shaped appendage. While this may have its attractions at the molecular level of operation, an electric motor/propeller combination would be more practical at the scale we are talking about.

2.3. Electromagnetic pump

This is a device with no moving parts that takes conductive fluid in at the front end and propels it out the back, in a manner similar to a ramjet, although with no minimum speed. It uses magnetic fields to do this. It would require high field strengths, which would be practical with high capacity conductors. At the scale we are talking about, room (or body) temperature ceramic superconductors are practical, making this a possibility.

2.4. Jet Pump

In this scenario, we use a pump (with moving parts) to propel blood plasma in one direction, imparting thrust in the opposite direction. This can either be done with mechanical pumps, or by means of steam propulsion, using jets of vaporized water/blood plasma.

2.5. Membrane propulsion

A rapidly vibrating membrane can be used to provide thrust, as follows: Imagine a concave membrane sealing off a vacuum chamber, immersed in a fluid under pressure, that is suddenly tightened. This would have the effect of pushing some of the fluid away from the membrane, producing thrust in the direction toward the membrane. The membrane would then be relaxed, causing the pressure of the fluid to push it concave again. This pressure would impart no momentum to the device, since it is balanced by the pressure on the other side of the device. At the macro scale, this thrust is not significant, but at the micro scale it is a practical means of propulsion.

2.6. Crawl along surface

Rather than have the device float in the blood, or in various fluids, the device could move along the walls of the circulatory system by means of appendages with specially designed tips, allowing for a firm grip without excessive damage to the tissue. It must be able to do this despite surges in the flow of blood caused by the beating of the heart, and do it without tearing through a blood vessel or constantly being torn free and swept away.

For any of these techniques to be practical, they must each meet certain requirements:

- The device must be able to move at a practical speed against the flow of blood.
- The device must be able to move when blood is pooling rather than flowing steadily.
- The device must be able to move in surges, so as to be able to get through the heart without being stuck, in the case of emergencies.
- The device must either be able to react to changes in blood flow rate so as to maintain position, or somehow anchor itself to the body so as to remain unmoving while operating.
- The device must be able to change direction laterally, so as to navigate the bloodstream.

From consideration of the above requirements, we can see that the most practical solution at present is one or more electric motors turning propellers. This solution is simple, well understood, and the technology has existed since 1960. The manufacturing techniques are relatively easy, as are methods for integrating it with the rest of the microrobot.

3. How do we know where the device should go?

The next problem to consider is exactly how to detect the problem tissue that must be treated. We need two types of sensors. Long-range sensors will be used to allow us to navigate to the site of the unwanted tissue. We must be able to locate a tumor, blood clot or deposit of arterial plaque closely enough so that the use of short-range sensors is practical. These would be used during actual operations, to allow the device to distinguish between healthy and unwanted tissue. There are many different types of sensors, each suited for different purposes. Another important use for sensors is to be able to locate the position of the microrobot in the body. This is particularly true in the initial scenario, where we will only have one device in the body at a given time. Without any way of determining location from internal references, we need to be able to track the device by external means.

First we will examine the various possibilities for external sensors. These will be at least partially external to the microrobot, and their major purpose will be twofold. The first is to determine the location of the operations site; that is, the location of the clot, tumor or whatever is the unwanted tissue. The second purpose is to gain a rough idea of where the microrobot is in relation to that tissue. This information will be used to navigate close enough to the operations site that short range sensors will be useful.

3.1. Ultrasonic

This technique can be used in either the active or the passive mode. In the active mode, an ultrasonic signal is beamed into the body, and either reflected back, received on the other side of the body, or a combination of both. The received signal is processed to obtain information about the material through which it has passed. This method is, of course, greatly similar to those used in conventional ultrasound techniques, although they can be enhanced greatly over the current state of the art.

In the passive mode, an ultrasonic signal of a very specific pattern is generated by the microrobot. By means of signal processing techniques, this signal can be tracked with great accuracy through the body, giving the precise location of the microrobot at any time. The signal can either be continuous or pulsed to save power, with the pulse rate increasing or being switched to continuous if necessary for more detailed position information.

In the passive mode, the ultrasonic signal would be generated by means of a signal applied to a piezoelectric membrane, a technology that has been well developed for at least a decade. This will allow us to generate ultrasonic signals of relatively high amplitude and great complexity.

3.2. NMR/MRI

This technique involves the application of a powerful magnetic field to the body, and subsequent analysis of the way in which atoms within the body react to the field. It usually requires a prolonged period to obtain useful results, often several hours, and thus is not suited to real-time applications. While the performance can be increased greatly, the resolution is inherently low due to the difficulty of switching large magnetic fields quickly, and thus, while it may be suited in some cases to the original diagnosis, it is of only very limited use to us at present.

3.3. Radioactive dye

This technique is basically one of illumination. A radioactive fluid is introduced into the circulatory system and its progress throughout the body is tracked by means of a fluoroscope or some other radiation-sensitive imaging system. The major advantage of this technique is that it follows the exact same path that our microrobot would take to reach the operations site. By sufficiently increaing the resolution of the imaging system, and obtaining enough data to generate a three dimensional map of the route, it would provide valuable guidance information for the microrobot.

The active form of this technique would be to have a small amount of radioactive substance as part of the microrobot. This would allow its position to be tracked throughout the body at all times. Additionally, since the technique would not require the microrobot to use any power, or require a mechanism of any sort, it would greatly simplify the design of the microrobot. While there are risks from radiation, the amount of radioactive substance used would not be even a fraction of the amount used in radioactive dye diagnosis. Additionally, as advances in electronic sensors continue, the amount of radiation needed for tracking would steadily be reduced. In fact, infrared sensing techniques are so advanced that we can fully shield the radioactive substance and merely track its heat directly.

3.4. X-ray

X-rays as a technique have their good points and bad points. On the plus side, they are powerful enough to be able to pass through tissue, and show density changes in that tissue. This makes them very useful for locating cracks and breaks in hard, dense tissue such as bones and teeth. On the other hand, they go through soft tissue so much more easily that an X-ray scan designed to show breaks in bone goes right through soft tissue without showing much detail. On the other hand, a scan designed for soft tissue can't get through if there is any bone blocking the path of the x-rays. Another problem with x-rays is that it is very difficult to generate a narrow beam, and even if one could be generated, using it to scan an area in fine detail would necessitate prolonged exposure. Consequently, x-rays are useful only for gross diagnosis, for which several of the techniques listed above are far better suited.

3.5. Radio/Microwave/Heat

Again, these techniques (really all the same technique) can be used in both passive and active modes.

The passive mode for the techniques depends on the various tissues in the body generating signals that can be detected and interpreted by external sensors. While the body does generate some very low frequency radio waves, the wavelength is so large that they are essentially useless for any sort of diagnostic purposes of the type we are interested in. The same is true of microwaves. Recent developments, however, in the technology of infrared detection, offer great promise in potentially improving our ability to detect tumors by the increased heat they generate as a result of their increased metabolic state. This technology, however, is in its infancy. We do not know enough about how different cells in the body generate heat to be able to say how useful the technique would be.

In the active mode, a signal is generated from outside the body and is treated the same way that ultrasonics or x-rays are; it is allowed to reflect from/pass through tissues and the result interpreted. However, only infrared has a short enough wavelength to be able to provide the required image resolution for accurate and detailed navigation, and a great deal of image processing would be required to filter out the natural background signal from the body.

In order to use the technique to track the microrobot, a signal would need to be generated by the microrobot, detected outside the body, and interpreted to obtain position information. This is only practical for infrared or higher frequencies could be useful to obtain sufficiently accurate positional information. Recent advances in infrared sensing technology make this more attractive than might otherwise be the case.

From the above discussion, we can come to the conclusion that there are two possible choices for our tracking system. We can either generate an ultrasonic signal and track that, or generate enough infrared or heat within the structure of our microrobot and track that. Of the two, the infrared technique is more practical, since there is far less problem of reflections and multi-path problems with infrared than with ultrasonics.

4. How do we control the device?

Next, we consider the case of internal sensors. When we say internal sensors, we mean sensors that are an integral part of the microrobot and are used by it to make the final approach to the operation site and analyze the results of its operations. These sensors will be of two types. The first type will be used to do the final navigation. When the device is within a short distance of the operation site, these sensors will be used to help it find the rest of the path, beyond what the external sensors can do. The second type of sensor will be used during the actual operation, to guide the microrobot to the tissue that should be removed and away from tissue that should not be removed.

4.1. Chemical

Chemical sensors can be used to detect trace chemicals in the bloodstream and use the relative concentrations of those chemicals to determine the path to take to reach the unwanted tissue. This would require several sensors so as to be able to establish a chemical gradient, and , for the same reason, would require a certain degree of physical separation between sensors. While this is not a strict requirement, the alternative would be to try every path, and retrace a path when the blood chemicals diminish. While it is not difficult to create a solid state sensor for a given chemical, the difficulty increases greatly when the number of chemicals that must be analyzed increases. Consequently, we would probably need a series of microrobots, one for each chemical, or at least a set of replaceable sensor modules. An alternative to solid state sensors is for chemical analysis is described next.

4.2. Spectroscopic

This would involve taking continuous small samples of the surrounding tissue and analyzing them for the appropriate chemicals. This could be done either with a high-powered laser diode or by means of an electrical arc to vaporize small amounts of tissue. The laser diode is more practical due to the difficulty of striking an arc in a liquid medium and also due to the side effects possible when sampling near nerve tissue. The diode could be pulsed at regular intervals, with an internal capacitor charging constantly so as to provide more power to the laser diode than the steady output of our power source.

4.3. TV camera

This method involves us having a TV camera in the device and transmitting its picture outside the body to a remote control station, allowing the people operating the device to steer it. One disadvantage of this technique is the relatively high complexity of the sensors. On the other hand, solid state television sensors are an extremely well developed technology, and it should not be difficult to further develop it to the level needed. This could be combined with the laser diode at low power used for illumination.

4.4. UHF sonar for resolution, texture

This technique would involve analyzing the return from an ultrasonic beam bounced off a nearby surface. This would give relatively low detail, and is dependent on the tissues in question having a sufficiently unique reflection. It would require either a great deal of onboard processing power or a very high communications bandwidth between the microrobot and the external systems; much more so than even the TV camera.

From the above it can be seen that the best choice for short-range sensors is the spectroscopic technique, for the following reasons:

The equipment required is all solid state with no moving parts. While there is a certain power requirement, this can be met by using capacitors to store energy over a period of time and discharge it quickly. Another advantage of this technique is that simply by adding power to the diode beam we are destroying the unwanted tissue, thus combining the sensory and treatment requirements into the same equipment. Samples of the blood plasma can be tested inside a closed chamber, which would give us the ability to do a chemical analysis that could detect a wide range of compounds rather than just one or two. Simply by doing chemical tracking with the sampling door closed, and cell analysis with the door open, we can combine both short range sensor requirements using one sensor.

5. Means of treatment

The treatment for each of the medical problems indicated above is the same in general; we must remove the tissue or substance in question from the body. This can be done in one of several ways. We can break up the clump of substance and rely on the body’s normal processes to eliminate it. Alternately, we can destroy the substance before allowing the body to eliminate the results. We can use the microrobot to physically remove the unwanted tissue. We can also use the microrobot to enhance other efforts being performed, and increase their effectiveness.

5.1. Physical removal:

This method can be effective in the treatment of arteriosclerosis. In this case, a blade, probe or edge of some sort can be used to physically separate deposits of plaque from the artery walls. The bloodstream would carry these deposits away, to be eliminated by the normal mechanisms of the body. Since it takes years before the plaque buildup reaches dangerous levels, the small amount not scavenged by the body can be regarded as not immediately significant.

In the case of blood clots, the situation is not so simple. In this case, it is possible that the action of physically attacking the clot could cause it to break away in large chunks, some of which could subsequently cause blockages in the blood flow. If we are going to do this, we need some means of preventing this from happening. We can set up some mechanism to catch these blood clots and further break them up, or we can try to tap into the circulatory system downstream of the clot and filter out the pieces. It behooves us to work out a technique that will crush the blood clot into pieces too small to a danger.

We can simply send the device to the site of the arteriosclerosis or blood clot, scoop away sections of it, and have the device carry the tissue out of the body where it can be dissolved/destroyed. Repeated applications of this technique could remove most or all of a tumor with minimal destruction to the surrounding tissue and minimal spreading. In fact, proper use of the sampling box described in the previous section could be effective if it is large enough; rather than remove the substances, we can place them in the sample box, destroy them, and then rely on the body to eliminate the ash..

In the case of tumors, the problem is more serious. The act of physically shredding or even just breaking loose clumps of cells can result in the cancer metastasizing throughout the body. Since the mechanism of cancer spreading is unknown, this is a real danger. One possible solution is, as in the case above, to filter the cancerous cells out of the blood immediately downstream of the tumor. Even if it is possible to distinguish cancerous cells from normal cells by filtering, this would not prevent the spread of tumor causing chemicals released by the ruptured cells. In this case, something more drastic is indicated. Again, use of the sampling box described above might be useful, since it does destroy whatever is placed within it. Unfortunately, the act of removing cancerous cells to place them in the box could be dangerous. This leads us to the next alternative.

5.2. Physical trauma:

Another way of dealing with the unwanted tissues is by destroying them in situ. This would avoid damaging the cancerous cells and releasing chemicals into the bloodstream. In order to do this effectively, we need a means of destroying the cell without rupturing the cell wall until after it is safe. We shall consider a number of methods:

Resonant microwaves/Ultrasonics

Rather than merely apply microwave/infrared or ultrasonic energy at random frequencies, the frequency of the energy could be applied at the specific frequencies needed to disrupt specific chemical bonds. This would allow us to make sure that the tumor producing chemicals created by cancerous cells would be largely destroyed, with the remaining amounts, if any, disposed of by the body’s natural defenses.

5.3. Chemical

At first thought, chemical means do not seem to effective, since the device could not carry large quantities of chemicals, and making many round trips to a chemical reservoir would be difficult. However, further consideration will reveal several possibilities.

The first is to use chemical agents of extreme potency. Since we would be able to apply the chemicals directly to the tissue in question, the side effects would be much less than if we rely on the bloodstream to carry the chemicals. A useful but not essential feature would be that they have a greater effect on the undesired tissues than on normal tissue. While this is the method used in chemotherapy for cancer, the side effects can be extremely debilitating. By delivering the chemicals in small amounts directly to the site where they are required, we could avoid most if not all of the side effects. This method could be used, although with lesser effect, to dissolve blood clots, and to dissolve deposits of arterial plaque. While it could be practical to release the chemicals at the operation site, it would not be practical, for time reasons, to inject the chemicals into each individual cell.

Another possibility is to introduce the chemicals directly into the bloodstream, but have our device affect the cancerous cells in such a way as to make them more susceptible than usual to the chemicals in question. This would allow lower levels of chemotherapy to have the same effect as the normal method, reducing the side effects and the strain on the patient. There have been a number of experiments done with electrical stimulation of cell walls that seem to have such an effect. In fact, we could combine the two techniques by bringing chemicals to the site and then applying an electrical stimulus to the surrounding area, enhancing the effectiveness of the chemical.

5.4. Heat

The deleterious effect of heat on cells is well documented. Consequently, the use of heat to destroy cancerous tumors would seem to be a reasonable approach to take. There are a number of ways in which we can apply heat, each with advantages and disadvantages of their own. While the general technique is to apply relatively low levels of heat for prolonged periods of time, we can apply much higher levels for shorter periods of time to get the same effect. This is more practical for us, since the scale of our microrobot is small enough to make applying heat over a large area for a long time difficult.

Microwave This is a popular method used in diathermy and other techniques. Microwave radiation is directed at the cancerous cells, raising their temperature for a period of time, causing the death of the cells in question. This is normally done by raising the temperature of the cells to just enough above body temperature to kill them after many minutes of exposure. In our case, this would require a means of generating a strong enough microwave signal in a package that is, frankly, pretty small.

Ultrasonic An ultrasonic signal, which can be generated by a piezoelectric membrane or any other rapidly vibrating object, is directed at, and absorbed by, the cells being treated. This energy is converted to heat, raising the temperature of the cells and killing them as previously described. This has a number of advantages for us over the microwave technique, including small size and simplicity of the generator. This would not be very effective against either blood clots or arterial plaque, neither of which is very susceptible to prolonged low heat.

Electrical resistance heating In this case, two electrodes would be placed in contact with a tumor, and a high electric current would be induced between the electrodes. This would literally cook the cancerous cells. It would not be very effective against arterial plaque or blood clots, neither of which is very conductive. It could, however, as mentioned earlier, be used to enhance the effect of chemotherapy as well.

Laser This would involve using a high-powered laser diode to burn away cancerous cells, arterial plaque and blood clots by vaporizing the unwanted materials. This is the method that would have the best chance of success against blood clots and arteriosclerosis as well as cancer cells. Of course, when I say heat in this case, I mean enough heat to vaporize tissue, not merely to warm it.

From the above we can see that there is no one best way of treating the unwanted tissue, since the method of treatment is different for each case. Rather than design a microrobot capable of all techniques, we will design a microrobot that can have any of several "treatment modules" installed on it, allowing the same basic design to be used.

5.5. Power

One major requirement for our microrobot is, of course, power. We have to be able to get sufficient power to the microrobot to allow it to perform all of its required operations. There are two possible paths we can take for this. The first is to obtain the power from a source within the body, either by having a self-contained power supply, or by getting power from the bloodstream. The second possibility is to have power supplied from a source external to the body.

6. Source within the body

There are a number of possible mechanisms for this scenario. The basic idea is that the microrobot would carry its power supply within itself. It would need enough power to move to the site of the operation, perform its functions, which might be very power intensive, and then exit the body. There are three basic scenarios for on-board power supplies.

6.1. Body heat

This method would use body heat to power the microrobot, in effect using the entire body as a power supply. The basic problem with this is that a power supply requires an energy gradient in order to function. In this case, we would need to areas of different temperature, so that we could set up a power flow between them. Since our microrobot would have to be mobile, and operate at full capacity in many different environments, this requirement would be difficult to fulfill.

6.2. Power from the bloodstream

There are three possibilities for this scenario. In the first case, the microrobot would have electrodes mounted on its outer casing that would combine with the electrolytes in the blood to form a battery. This would result in a low voltage, but it would last until the electrodes were used up. The disadvantage of this method is that in the case of a clot or arteriosclerosis, there might not be enough blood flow to sustain the required power levels. Also, if the electrodes were ever embedded in anything that blocked their access to the blood, power would drop to zero and stay there. This means that a backup would be required.

The second way to get power from the bloodstream is by means of a fuel cell, or simply by burning blood chemicals. This is similar to a battery except that rather than obtain power from current flow between electrodes, we would obtain power by causing chemical reactions to take place at a controlled rate and obtaining power from this. This is much the same way that the body gets its own power by consuming fuel chemicals from the bloodstream. This has the same problem as the electrode method; it will stop working if access to the blood is blocked, or if the chemicals are not replenished.

6.3. Carry the full amount of energy required directly onboard

The third method is simply to carry the full amount of energy required directly onboard. The first case is one in which we use conventional chemical batteries. Unfortunately, the power to weight ratio of chemical batteries is extremely low, and a battery of such small size would be of limited use.

The second method is to use high-voltage capacitors to store a charge and use it gradually. As capacitor technology improves this may become practical, but at the moment the power to weight ratio is again too low. If we could manufacture body-temperature ceramic superconducting power storage coils (a distinct possibility, given the scale involved), this method becomes very attractive.

The third, and by far the most practical method, is to use an onboard nuclear power source. This would be relatively easy to shield given the amount of fuel involved, and it has other advantages as well. For one thing, the same radioactive material could be used for power and tracking, since the casing must be hotter than body temperature to produce power. This would have the effect of greatly reducing the complexity of the microrobot. For another, there would be no worries about running out of power, or insufficient power to get the job done. At the micro scale, shielding and power conversion are relatively easy, making this method extremely practical. The only major problem with this method is the social and political objections that would take place.

6.4. External to the body

In this case, the power would be transmitted to the microrobot from outside the body. This can be done in a number of different ways, but it boils down to two possibilities. The first is to transmit the power by means of a physical connection, and the second, of course, is to transmit it without a physical connection.

6.5. Physical connection

In the first case, we would need some sort of wire or cable to carry power between the microrobot and the outside power source. There are a number of problems with this approach. The first, of course, is that the wire needs to be able to reach inside the body to where the microrobot is. This means that it must be thin enough to fit down every blood vessel that the microrobot can enter. If the wire is deployed from outside the body, the friction of the outer casing must be low enough to allow the wire to move freely within the blood vessels without cutting into the walls at any change of direction. The wire must also be flexible enough to be able to withstand abrupt changes of direction without fatiguing, kinking or breaking. If the wire is deployed from the microrobot, we must have enough stored on the microrobot for it to be able to reach all the way to the operating site. We must also have a means of deploying the wire with! out tangles, and a means of retracting it back into the microrobot. Of course, if the wire is strong enough, it would greatly ease our movement problems, since the microrobot would then be deployed on a tether, with only navigational capabilities required, rather than long range movement. Similarly, removing it from the body would be greatly eased since it could simply retrace its path.

The next question is how the power would be transmitted. There are two possibilities: electricity and light.

In the case of electricity, we must take several factors into account. The first is that the electricity needs a return path. This means that we must deploy a two-conductor cable, or use the body itself for the return path. Given the small amounts of power required, this is possible. Another consideration to take into account is that due to the small diameter of the wire, there would inevitably be some heating of the wire, and therefore the surrounding tissue and this would have to be taken into account. The blood, of course, would act to carry away most of the heat. We could also use the wire for high-speed two-way communications, making that job much easier.

If the power is transmitted in the form of light, which is then either used directly or converted to electricity, the problems are different. There is no requirement for a return path, nor is there any significant leakage along the length of a fiber-optic cable of such a short length. On the other hand, the problem of brittleness is much more significant at the diameters required. This is especially true if the fiber-optic cable is stored in, and deployed from, the microrobot itself. There is also a problem in that the conversion of light to electricity would require more on-board equipment.

6.6. Microwave

In this case, there would be an antenna built into the physical structure of the microrobot. Microwave energy would be beamed into the body, where it would be picked up by the onboard antenna and converted into electricity. The first problem, of course, is readily apparent; most of the microwaves will be absorbed by the conductive body fluids, causing a great deal of ancillary damage. While microwave ovens work by agitating water molecules, and heating food that way, the fact is that any microwave beam directed at the body will be largely converted to heat.

6.7. Ultrasonic

This technique is similar to that of the microwaves, except that since water is such a good conductor of sound, most of the energy would not go into heating up the tissues in the path of the beam. Instead, they would tend to dissipate, and would be absorbed by the body as a whole, with much less attendant danger. A piezoelectric membrane would be used to pick up the ultrasonic waves and convert them to electricity. This membrane, of course, could be modulated at the same time to act as a communications device (two-way) and for a sensor device, as well.

6.8. Induced magnetic

In this case, the body is surrounded by a magnetic field. This field would induce currents within a rotating closed conducting loop in the microrobot, which it would then use for power. The frequency of the resulting power is dependent on the rotational speed of the pickup loop, and so alternating the rotational frequency (mechanical FM modulation) would provide a communications path as well. By switching the current through a relatively high resistance path, we would obtain a pinpoint heat source, which could be used for treatment as well.

From the above descriptions, we can see that if we can maintain the physical connection, a wire deployed from the microrobot itself would be very useful, and solve many of the problems we would encounter. However, if no physical connection can be maintained, either ultrasonics or magnetic induction could be used, with ultrasonics appearing to be somewhat more effective.

6.9. Control system

We need to steer the microrobot to where the sensors tell us it needs to be. As always, the two choices are internal control and external. The following are considerations:

Need to know where to go

This does not necessarily mean that we have a detailed map of the body that the microrobot is following. It simply means that the microrobot must be able to proceed to the location of the unwanted tissue within the specified time constraints, if any. If the microrobot is permanently introduced into the body to circulate and remove unwanted tissues as they are detected, this requirement is largely unnecessary.

Need to know the route

This is different from the above requirement in that some places are more difficult than others to reach. For example, a tumor deep within the brain can be located by various means, but it cannot be accessed by conventional surgical techniques. We may be able to locate the tumor by means of conventional techniques, but the sequence of blood vessels that we need to follow may be more difficult to determine. Again, for a maintenance routine, this requirement may be unnecessary as long as the microrobot covers the entire bloodstream, or at least all the sections that it can access, in a reasonable time.

The first is when a preplanned route exists and must be followed. Due to the complexity of the circulatory system, this will generally be the case only when the tumor can be accessed from the larger and more obvious blood vessels.

The second scenario is when the microrobot is using long range sensors, specifically chemical sensors, to locate the tumor. In this case, the microrobot would be functioning in a manner similar to a bloodhound. A reduction of the chemical trail used to locate the tumor would indicate a "wrong turn" in the bloodstream, and the need to backtrack to the point where the chemical traces started to diminish. In this case, we must also be sure not to be fooled by eddies in the bloodstream that cause a momentary reduction of the chemicals that are detected.

Need to be able to apply treatment effectively

Once we have reached the location of the tumor, clot or deposit of arterial plaque, we must be able to apply the appropriate treatment without making matters worse. We do not want to cause tumor producing chemicals or cells to scatter throughout the bloodstream. Similarly, we do not want clots to break up into large chunks, precipitating the very strokes we are trying to prevent; nor do we want to pierce the wall of an artery rather than simply remove plaque deposits.

In the case of semi-permanent introduction of the microrobot into the bloodstream for maintenance purposes, the problem is the exact opposite; we want to avoid the removal of the microrobot from the body unless it is done deliberately. One way of doing this is by means of chemical sensors. When the chemicals that accompany the breakdown of platelets and the formation of a blood clot are detected, the microrobot would swim "upstream"; away from the clot formation. Of course, the microrobot is supposed to seek out clots in order to destroy them. We would have to find some way of distinguishing between clots that are caused by an opening in the circulatory system large enough for the microrobot to exit, and those that are small and growing only gradually. This is especially true since if we do not distinguish between them, the microrobot will constantly be breaking up clots around a wound and reopening it, causing a particularly ironic form of hemophilia.

Need to compensate for the unexpected

Certainly while the techniques are being developed, there will be many unexpected events. Even after the control techniques are perfected, there will be many occasions where it will be necessary to have external decision making introduced into the control loop; i.e. we are not going to be creating an autonomous microrobot any time soon. There are two ways we can handle this problem. Either the microrobot is autonomous for simple things, and calls for help when something unexpected happens, or it can be completely externally controlled, greatly reducing the complexity of the on-board processing power.

The above requirements cannot even be met for a car navigating in a city, which is a similar but much less complex problem. However, not all of these requirements are entirely binding. Let us consider each one in sequence.

The only real thing that we need to know about where to go is that there is tissue to be treated along the route from introduction to egress of the microrobot. This can be accomplished in several ways. Introduction of the microrobot into the bloodstream at the correct point will allow it to move to the target by means of simply following the blood vessels appropriately. In a maintenance program, the microrobot does not even need a destination, but simply goes where it will while trying to sense target tissues and act appropriately. While it would be more effective to know the shortest or most effective route to the target tissue, this is only a constraint if there is a time constraint as well. For a maintenance routine, it does not matter where the microrobot is, although a chemical tracking system of some sort would improve performance greatly over random sampling. If we do not have a specific location as goal, we need not worry about the route, save that w! e do not want the microrobot to wind up in some sort of eddy with no escape. For that matter, we do not want it to wind up embedded in the wall of a vein, or in a sludge of arterial plaque. We do need some means of detecting and avoiding such an occurrence.

We can see from the above that even though we have reduced some of the control requirements for our microrobot, the remaining considerations are well beyond the capabilities of modern programming techniques. If we had thousands or millions of nanorobots in the bloodstream, this would be a serious obstacle. However, with only a very few microrobots to control at once, we can actually (assuming sufficient communications bandwidth) have a person controlling the microrobot directly.

7. Means of recovery from the body

Given sufficiently accurate control of the nanomachine, or a tether, this is not a problem; we can just retrace our path upstream. However, it would be a lot easier, and recommended, to steer a path through the body that traverses major blood vessels and winds up at a point where we can just filter the nanomachine out of the bloodstream. This will reduce the possibilities for difficulties, and also cause less wear and tear on the nanomachine. Of course, either scenario is a possibility, depending on where the actual operation site is. Another possibility is to have the nanomachine anchor itself to a blood vessel that is easily accessible from outside, and perform a small surgical operation to remove it.

8. Other Applications (the year after next)

8.1. Kidney stones

As anyone who has ever been plagued by kidney stones can attest, they are extremely painful, as well as being difficult to treat. In most cases, the pain must be endured until the stones have been passed. Attempts can be made to break up the stones by means of high intensity ultrasonics, but these attempts are difficult and not very successful.
By introducing a microrobot of the type described in this paper into the urethra in a manner similar to that of inserting a catheter, direct access to the kidney stones can be obtained, and they can be broken up directly. This can be done either by means of ultrasonics directly applied, or by the use of a laser or other means of applying intense local heat to cause the stones to break up. If these techniques do not work, direct physical force by means of a sintered tungsten carbide cutting or abrasive surface could be used.

8.2. Liver stones

Liver stones accumulate in the bile duct, and while they are nowhere near as painful as kidney stones, they can still cause serious health problems. Microrobots of the above type can be introduced into the bile duct and used to break up the liver stones as well. By continuing on up the bile duct into the liver, they can clear away accumulated deposits of unwanted minerals and other substances as well. This of course, is true for the kidneys as well.
Gout

Gout occurs when the breakdown products of various fats cannot be removed from the bloodstream by the kidneys. These byproducts tend to crystallize at or near the joints, notably in the lower extremities, and cause excruciating pain to those who suffer from it. When a microrobot is in the bloodstream, it can locate these deposits by means of a combination of chemical sensors and external tracking, and can break up the crystals, allowing the bloodstream to carry them away. Of course, this will in no way prevent recurrence of the problem, but it will alleviate the symptoms for a time.

8.3. Burn and wound debriding

The microrobots can also be used to clean wounds and burns. Their size allows them to be very useful for removing dirt and foreign particles from incised and punctured wounds, as well as from burns. They can be used to do a more complete and less traumatic job than conventional techniques.

8.4. Parasite removal

The microrobots can also be used to attack other life forms in the body. For example, they would be well suited to deal with such parasites as heartworms (hopefully in pets rather than humans), liver flukes (definitely in humans). As the sensor technology improves, they could be used to attack various bacteria and other smaller organisms as well, although this would probably require the introduction of large numbers of the units into the body. In essence, this would be creating artificial antibodies, and while this is the logical extrapolation of the technology, it will not happen for some time.

8.5. Remove or break down tar, etc in lungs

If the units are operating in maintenance autonomous mode, they could be very useful for the treatment of dirty lungs. This could be done by removing particles of tar and other pollutants from the surface of the alveoli, and placing them where the natural processes of the body can dispose of them. Alternatively, the unwanted substances could be vaporized or otherwise reduced to their component elements. This would require a microrobot capable of moving within the lungs, on alveolar surfaces as well as over the mucus layer and over the cilia within the lungs.

9. Conclusion

As can be seen from the above, most or all of the engineering technologies to create a series of practical and effective microrobots already exist. Rather than keep our eyes fixed on the far future, let us start now by creating some actual working devices that will allow us to cure some of the most deadly ailments known, as well as advance our capabilities directly, rather than as the side effects of other technologies. A concerted development effort could have a working model of the microrobot ready within a year or two, and this would certainly advance the development of nanotechnology.

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