Engineering in Medicine

Medicine is an ancient practice. We have had doctors for as long as we have had civilisation. However the success that doctors have had in treating disease has taken great leaps forward when engineering processes have allowed effective, safe and successful procedures to be standardised. An engineer is set apart from a scientist in the way that – rather than conducting research to make discoveries – she observes scientific discoveries and then breaks them down into to their most basic principles so that she can understand both the possibilities and limitations of the discoveries. She then takes these principles, modifies them in order to apply them to another situation, and standardises the process. I believe that advances in the quality of medical treatment available are entirely dependent on this engineering input and that without engineers we wouldn't enjoy the quality and length of life which we currently do.

Within my essay, I will look at three different types of collaboration between engineering and medicine: the effect of interaction between engineering design processes and medical research to mass produce medical products, the application of medical standards on existing engineering technology to rebuild the human body and the new integrated approach between medical researchers and engineers to design treatments on a molecular level. I believe that all three types of interaction have had a fundamental impact on today's medical landscape.

The first stage in medical treatment is to establish the underlying problem. For centuries doctors have made diagnoses based solely on the symptoms that the patient showed and their intuition, which was both imprecise and inaccurate. However, by applying discoveries in the physical sciences to medicine, engineers have given doctors a range of tools to promote far more accurate diagnosis and safer medical practices.

For example, on the 22nd December 1895 the German physicist and mechanical engineer Wilhelm Röntgen discovered x-rays and illustrated them with a picture of his wife's right hand. The response to Röntgen's discovery was one of widespread curiosity, with this new phenomenon being used to take radiographs of all manner of objects.

Dr John MacIntyre (who originally trained as an electrical engineer) also marvelled at Röntgen's discovery. However MacIntyre didn't focus on the novelty of the x-ray photographs but instead on the image of the previously invisible skeleton that the x-rays produced. MacIntyre took the principle of x-rays and built a machine that could be used quickly and repeatedly to image medical patients; effectively mass producing the radiograph. This design of x-ray machine allowed MacIntyre to open the world's first ever radiology department at Glasgow Royal Infirmary only three months after Röntgen's initial discovery.

In order to industrialise radiology so that it could be used in medicine MacIntyre had to solve two key problems: how to consistently produce x-rays and how to control the exposure time and the direction in which the x-rays were emitted. He did this by accelerating high energy electrons and emitting them from a heated cathode towards a metal plate on top of an anode. When the electrons hit the metal plate they emitted x-rays which were directed at the patient through an aperture in a dense metal plate. Due to their high energy the x-rays were absorbed by the more dense body tissues such as bones (or soft tissues that had been injected with a contrast medium) but passed through less dense body tissues; allowing the x-rays to reach the photographic plate where they reacted with the silver halide crystals in the gelatine emulsion on a piece of photographic film, creating an image of the tissue structure of the body.

MacIntyre's original x-ray machine worked in much the same way that current x-ray machines work. However engineers work on the principle of breaking down a process and then systematically and repeatedly rebuilding the process with slight variations each time in order to improve it, so it is common for engineers to build upon the work of their predecessors. In terms of the x-ray machine this innovation came in 1972 the British engineer Godfrey Hounsfield and the American physicist Allan Cormack enhanced the original design to create the Computerised Tomography (CT) scanner. Hounsfield and Cormack added a curved slide for the x-ray machine to sit on and a computer as well as replacing the photographic film with x-ray detectors. Allan and Cormack's new design enabled many 2D radiographs to be digitally layered on top of one another from many different angles to create a virtual 3D model of an organ.

This improvement modernised MacIntyre's original device machine for the digital age where data could be shared wirelessly and far more quickly as well as further increasing the precision of the images that could be produced and the accuracy of the representation of internal damage. This commercialisation and standardisation of x-ray and CT scans along with fluid testing and magnetic resonance imaging has increased the rate of diagnoses for all medical conditions; saving time and ultimately saving lives.

From an engineering perspective, probably the most surprising aspect of the story of the x-ray machine was the extremely short time period between the first image and the creation of a machine that could mass produce radiographs. Conversely, in the case of sterilisation it was not until two thousand years after Hippocrates noticed that pouring boiling water onto surgical instruments improved patients' chances of survival that the French microbiologist Charles Chamberland (who was working closely with Louis Pasteur on the germ theory of disease) saw the potential provided by a pressure cooker, a device then used for braising meat, to develop a machine that could sterilise surgical equipment. The autoclave was born.

In 1879 Chamberland faced two major issues in designing the autoclave, the first of which was how to completely sterilise medical equipment. Chamberland applied Hippocrates' observation and subjected the objects inside the autoclave to a very high energy environment. This environment would transfer energy to enzyme molecules within the microorganisms, causing the enzymes to vibrate very vigorously until their chemical bonds broke. Without enzymes chemical reactions within the microorganism cannot take place at a sufficient rate to sustain life; causing the microorganism to die. Chamberland was now faced with his second problem: how to carry out the sterilisation process at a sufficient rate to make the autoclave economical. Since air is a poor transmitter of energy, an air-based autoclave would take over two hours to completely sterilise the equipment inside it. To fix this, Chamberland used a pump system to remove the air from the autoclave and replace it with pressurised steam at a temperature of ~130°C, meaning that the sterilisation process only took 15-20 minutes, depending on the size of load.

As with MacIntyre's repurposing of Röntgen's illustration, Chamberland's genius was to see the potential that a pressure cooker to be a sterilisation device. Chamberland's autoclave was set apart from the sterilisation techniques of Hippocrates and his other forerunners in that his autoclave achieved complete sterilisation every time it was used by standardising and controlling the temperature and pressure of the steam.

The exacting and controlled technique of Chamberland's autoclave meant that it has become a standard piece of equipment in any medical environment. The autoclave also stopped surgery from leading to a dangerous infection, making it a safe and successful treatment option for an enormous range of medical conditions.

Once engineers had collaborated with scientists to produce and standardise accurate and safe diagnostic techniques, the next medical challenge became to replace body parts or aid their repair. Every year many patients suffer because their body parts stop working effectively due to degradation or breakage; a common example of this is osteoarthritis in hip joints. The root cause of these conditions is that human bodies do not come with spare parts in case one ever needs to be replaced. However, the principle of making replacement parts for machinery is central to engineering, for example replacing a broken part in an engine. Therefore, over the last century engineers have worked to apply the principle of component replacement to medicine by taking existing engineering technologies and repurposing them for medicine.

When engineers were first designing medical implants in the 20th century they knew what functions their implants had to carry out but could not find a material with the right combination of qualities to do so. An example of the severity of this problem was in 1895 when Dr Lane had to remove the first ever internal fixation plate after it began to corrode whilst attached to the patient's leg bone. Engineers therefore had to look for a material with the following combination of properties:

- Compressive strength – the implant must be strong enough to not break under the weight of the body but also be able to bend in a similar way to bone when under large stresses
- Toxicity – the implant must be non-toxic otherwise it would kill the very patient whose life it is meant to improve
- Reactivity – the implant must not corrode in the body's internal environment
- Price – in order to use medical implants on a large scale they must be cost effective
- Weight – the implant must try to be similar in weight to its bone counterpart so that there is minimal discomfort to the patient.

Engineers had their first major success with vitallium, an alloy comprising mainly cobalt, chromium and molybdenum. Vitallium was developed in 1932 and has been used in the production of artificial hips ever since along with titanium.

Whilst the introduction of suitable materials improved the medical implant industry, implants were still being produced in a one-size-fits-all manner. Although this gave the highest rate of production and worked well for more generic procedures such as hip replacements, there are a range of diseases, such as types of bone cancer, whose treatments leave patients without large sections of their skeleton, the exact shape of which can vary greatly from person to person.

Engineers solved this problem by applying 3D printing technology to medicine. The major milestone in this personalised medical implant technology came in 2015 when a Spanish man received a 3D printed titanium sternum and ribcage that had been designed using CT scan data to replace his original sternum, which had been cancerous.

By taking a common engineering idea – replacing broken machine parts – and applying advanced materials technology to it, engineers have provided treatments for many common (and previously untreatable) diseases. And, by combining 3D printing technology with medical imaging and understanding, engineers are ushering in a new era of highly personalised and more successful implant treatments and even the possibility of growing organic tissue for implantation.

To date, the work of engineers in medicine has been solely focussed on improving diagnosis techniques and treatment technology by either repurposing scientific phenomena or by applying medical standards to existing technology to treat the sufferers of disease. However, a new type of coordinated collaboration between engineers and medical researchers is currently emerging which takes a proactive stance against disease by way of gene editing.

Gene editing has been possible since 1970s; one of its first large scale uses was to genetically engineer bacteria to secrete human insulin for treating type-2 diabetes. However the production of genetically engineered organisms was difficult and had a very low success rate – preventing it from being useful for human use.

A major breakthrough came in January 2013 with the development of the CRISPR-Cas9 gene editing system; which, from an engineering perspective, is a modified reapplication of a bacterial immune system's mechanism for fighting viral infection.

In the CRISPR-Cas9 molecule engineers combined a piece of guide ribonucleic acid (RNA), which is a molecular targeting mechanism, and a Cas9 protein, which is designed to cut DNA. CRISPR-Cas9 is far more useful for carrying out genetic engineering than previous gene editing technologies for three main reasons. Firstly, CRISPR-Cas9 is far more precise than previous editing techniques. This is due to its piece of guide RNA, which can be designed to bind to a specific gene by giving it a specific base sequence; and the Cas-9 protein, which cuts out only the section of DNA that the RNA has bound to. Secondly, CRISPR-Cas9 is far more efficient than previous techniques – the targeting of the guide RNA means that the CRISPR-Cas9 system will always find its target gene if it is present. Thirdly, it is relatively easy to mass produce CRISPR-Cas9 molecules to target many different genes as only a short piece of the guide RNA must be changed, making it far more economical than other gene editing systems.

The CRISPR-Cas9 system heralds a new dawn for medical treatment using genetic engineering. An article published in the Nature scientific journal in 2016 reported the successful use of CRISPR-Cas9 to remove HIV-1 genes from human T-lymphoid cells; showing that a cure for HIV, which is one of the world's most deadly diseases, could be only a few years away. However, the advent of gene editing shows that our engineering ability is becoming so advanced that it is now raising ethical issues that we had never previously dreamed of. As a society we must discuss the ethical implications of using such advanced engineering technology to make permanent genetic changes which can redefine whole species and put regulations in place to make sure that gene editing technology is not misused. But, if genetic engineering becomes an accepted form of medical treatment, the work that has already been done by CRISPR-Cas9 suggests that there are endless possibilities of what engineers and medical researchers working in tandem could achieve.

Overall, there is an intrinsic connection between the level of medical care that doctors are able to provide and the level of engineering input there has been. Engineers have had, and are having, a major effect on all of the stages of medical intervention, from preventing illness, to diagnosing diseases, to treating a huge spread of medical conditions far more quickly, accurately and safely than before. This is because, in my opinion, the definitive trait of an engineer is to take information and technology from one scientific field and apply it to another area, in this case medicine, in order to drive innovation and create a final product which would not originally have been achieved due to the traditional barriers between the different scientific areas.

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