**The Newnham Engineering Prize 2016-17**

**Engineering in Medicine**

Biomedical engineering has massively revolutionised patient care in the past few decades. We have not only seen improvements in surgical procedures but also the diagnosis and treatment of diseases. This field of engineering has been responsible for early diagnosis of various diseases and improvements in the treatment of countless conditions which previously would have led to death. In this essay I will be discussing some of the engineering feats that have advanced different sections of medicine; for example, surgical procedures, medical devices and machines that have facilitated the diagnoses of diseases and their treatment.

Robotic surgery is an excellent example that has been facilitated by biomedical engineering. Amongst this, the da Vinci system may be the most renowned. The da Vinci robot can assist surgeons during complex operations, but can also offer new surgical methods which conventional methods cannot: for example, enhanced precision, vision and control [1]. Such robots are having an increasing role in the surgical management of many cancers such as those of the prostate, kidney, cervix and throat amongst others. The surgical robot has also had applications in other fields of medicine including the treatment of cardiac diseases [2].

The da Vinci robot comprises of 2 main components: a surgeon console and a patient bedside cart that provides the instruments for the robot [3]. These two are just a few feet apart and connected by cables. The surgeon sits at the console and able to view high definition 3-dimensional images of the internal organs and anatomy. These images are produced with the use of a telescope inserted through one of the ports which can image internal organs at close proximity. Two side-by-side viewing channels are used within the same telescope to produce 3-dimensional images. The two slightly different images are projected separately on the binocular viewing screens on the surgeon's console. The 3D image can also be magnified by x10 the original size to help the surgeon manipulate smaller areas with more precision and accuracy [4].

Special fine instruments such as tissue graspers or scissors are inserted into the patient through narrow channels, called ports, which are between 8-12mm in diameter. The tips of these instruments can be manoeuvred with a high degree of freedom and the surgeon controls this at the console using joysticks. The surgeon also has foot pedals that control the instruments placed into the abdomen of the patient. Using these pedals the surgeon can apply diathermy to the tissues which is a special electric current that can burn tissues in a controlled fashion so as to coagulate tissues and especially blood vessels in order to stop bleeding at surgical sites.

Smaller incisions reduce pain and this drastically reduces the recovery time for the patient post operatively [6]. It also reduces the risk of wound infections and gives much better cosmetic results. Fine precise surgery allows for less blood loss during the procedure. These are just some of the advantages of da Vinci robotic surgery for the patient. For the surgeon, the advantages include operating in a comfortable sitting position with enhanced visualisation of the internal organs and this reduces physical and mental strain and thus reducing the risk of error and fatigue. The small instruments with degrees of freedom in excess of the human hand allows the surgeon to complete more complex tasks which human hands wouldn't be able to do [4]. If the surgeon suffers from a tremor then the da Vinci robot can filter this out almost completely so that none of this is translated to the fine instruments inside the patient.

In theory, using the da Vinci system, a surgeon sitting at the console could control a patient bedside cart attached to a patient who is half way across the world. This is remote telesurgery. However, the current disadvantage to this concept is that it suffers from latency (the time delay between the simulation of the joysticks and the movement of the robotic arms). Remote telesurgery is currently not practiced widely as surgeons normally work in the same room as the patient in case of a surgical emergency. It should be noted that the bedside cart with the robotic arms attached to instruments inside the patient is not autonomous. It can only move if the surgeon at the consoles simulates the movements. Therefore, the robot cannot operate by itself and make the surgeon redundant.

Overall, the invention of the da Vinci surgical robot is an example of how engineering can improve medical operations and ultimately enhance patient outcomes by reducing pain, risk of infections, blood loss and trauma to the patient. It shortens the recovery and allows the patient to be discharged within 24 hours and return to work much sooner.

However, this technology is still relatively new and suffers from some disadvantages. Firstly, it is very expensive (can cost approximately £2 million) putting it beyond the reach of some hospitals and secondly, this equipment is very advanced, so surgeons need a lot of training before they are able to operate with it.

Another great example of the application of biomedical engineering is in the field of diagnostics. Amongst some of the most important developments in this field would be the ultrasound machine that is now so universally used in the assessment of diseases and the monitoring of fetal development.

Sonography, also known as ultrasound imaging, uses a small transducer to emit ultrasonic waves. These high-pitched sound waves, beyond the range of human hearing, are later collected as echoes after they have rebounded from internal tissues. The computer interprets these echoes to create an image of the internal structure of the human body. Ultrasound scanning uses the same principle as sonar and is a technology that flourished after the Second World War when it was used to detect sea mines.

The main feature of the ultrasound machine is the transducer probe. It uses the principle of the piezoelectric effect to create and receive sound pulses. The transducer probe contains quartz crystals, also known as piezoelectric crystals [8]. These crystals can create sound pulses when an electric current is applied to them, and, in reverse, can create electric signals when sound waves hit them. The transducer probe emits sound at a frequency of 1 to 8 MHz depending on the depth of penetration required and the echoes returning from tissues are translated into electrical signals by the probe and relayed to the CPU which processes this raw data to create a grayscale image which is displayed on the screen [9]. The amplitude (loudness), frequency (pitch) and the time taken for the echo to return to the probe are all altered by the composition of the body tissue under the probe and this information is used by the CPU to compose the image.

The most common form of sonography displays cross-sectional images in two dimensions (2D). Three-dimensional (3D) ultrasound images are created by acquiring several 2D images, which are then combined using specialised computer technology to form a 3D image. Doppler ultrasound is based on the principle of the Doppler Effect. If the boundary reflecting the sound waves is moving, then the frequency of the echoes it is reflecting changes. Echoes are at higher frequency when the object is moving towards the probe, whereas they are of a lower frequency when the object is moving away from the probe [8]. This information about moving tissues is superimposed on the grayscale cross-sectional images as coloured pixels. In practice, most of the coloured pixels represent the movement of blood cells in vessels and it therefore displays blood vessels. Doppler ultrasound is mainly used to measure the rate of blood flow through arteries or the heart.

Ultrasound scanning helps to investigate common symptoms and signs, such as swellings and pain. The most well known application of ultrasound scanning is in pregnancy. It can be used to establish that the fetus is growing in the right organ (uterus and not fallopian tube), measure the size of the fetus to an accuracy of a single decimal place in millimetres allowing the eventual date of delivery to be estimated, detect miscarriages, find anatomical problems in the fetus such as cleft lip, help identify fetuses that may be affected with chromosomal abnormalities such as Downs Syndrome, monitor the growth of the fetus, detect whether the placenta is in an abnormally low position which would prevent safe natural delivery, and find the orientation of the fetus just prior to birth [10].

Another area in which sonography is used is in echocardiography. Echocardiography uses 2D, 3D and Doppler ultrasound to create images of the heart. Echocardiography is the most widely used form of diagnostic imaging in cardiology as it can be used for diagnosis, management and follow up of patients with suspected or known heart diseases [11].

Overall, the main benefit of ultrasound scanning is that it is non-invasive and generally not painful. It is a relatively inexpensive and easy-to-use imaging method. It can form clear images of tissues unlike conventional x-rays [9]. Furthermore, sonography is very safe as it doesn't use ionising radiation (X-rays) to create images of the internal body structure. However, ultrasound is energy and when focused and used at a high intensity, there can be a development of heat locally.

Sonography does have some limitations. Ultrasonic waves are disrupted by gas or air and so it isn't ideal for imaging gas-filled organs such as the lungs or bowel. Furthermore, great amounts of tissue (large stores of fat) can attenuate the sound waves and can degrade the images produced [9].

Another example of successful biomedical engineering is magnetic resonance imaging (MRI). It creates detailed images of the human body. It utilises radio waves, magnetic fields and field gradients to generate anatomical images of the human body. MRI can diagnose a variety of conditions ranging from tumours and strokes to spinal cord injuries [13]. It is also used to measure brain functionality and structure.

The human body is about 60% water. Hydrogen atoms found in water molecules are the central targets for MRI scanning. These atoms are randomly spinning on their axes, until a magnetic field is applied, which causes the hydrogen nuclei (which have a strong magnetic moment) to align in the direction of the field. Since half of the nuclei align in opposite directions, the majority of them cancel each other out. A radio frequency (RF) which is specific to hydrogen is applied. The RF pulse forces unmatched protons to spin at a particular frequency and direction [12]. The specific frequency of resonance is known as the Larmour frequency, which is calculated from the tissue being imaged and the strength of the magnetic field [12]. When the three gradient magnets are turned on and off rapidly they create a variable magnetic field. Hydrogen nuclei return to their natural alignment and spins and release the energy absorbed from the RF pulses, when the RF pulse is removed. This released energy from nuclei is detected by coils and sent to the computer as mathematical data [12]. The computer converts this data into 2D images or 3D models.

The electro-magnet is the predominant part of the machine. It produces a large and stable magnetic field of (0.5-2 tesla). Superconductivity can be applied to the technology of the magnet. The electro-magnet is surrounded by coils which transmits current. Strong magnetic fields require a lot of energy and some of this is dissipated as heat due to resistance. As a result, the wires are bathed in liquid helium (at -269'C) which is insulated by a vacuum to allow there to be zero resistance in the wires [12]. This technique allows the machine to be economically viable to operate. Two other types of magnets are used in MRI systems but to a lesser extent: resistive and permanent magnets. Resistive magnets have similar properties to superconducting magnets, except for the fact that they are not surrounded by liquid helium. Because of this, more energy is required, so a weaker magnetic field is used during this process. The MRI machine also contains three gradient magnets. These interact with the main magnetic fields to produce a variable magnetic field [12].There are also coils to emit RF pulses into the patient’s body.

The functionality of MRI can be extended in other specialised ways, using the properties of water molecules. As these are constantly diffusing in tissues, any impedance to their diffusion can be detected by a technique called diffusion MRI. Tumours are notorious in causing this impedance and therefore make themselves visible with diffusion MRI [13].

Another form of MRI is functional MRI which measures brain activity. When neural activity increases, the amount of oxygen consumed increases in that area [13]. Changes in blood oxygenation and blood flow can be detected by MRI and facilitate real-time activity maps to show which parts of the brain are being used in response to external stimuli. Oxygen is delivered to the brain cells using haemoglobin. Oxyhemoglobin and deoxyhemoglobin have different magnetic properties which interact with the strong magnetic fields. Consequently, the different types of blood can be differentiated and displayed differently [14].

MRI does not use ionising radiation. Amongst its other advantages over x-rays is that it can detect swelling and inflammation [15]. Unlike other diagnostic tools, MRI scans show detail in the soft tissue structures. Furthermore, it can show how blood flows through certain organs and vessels. This helps to detect problems resulting from blood circulation and blockages [15].

MRI scanners are very expensive. Each machine can cost over a few million pounds, so the NHS is therefore limited to the number of machines that it can afford [15]. Because of this, if a patient’s condition isn't urgent, then they could wait up to several months for an MRI scan.

The use of a very strong magnetic field introduces some disadvantages. Some magnetic metal implants can pose a hazard as they can move or heat up when they are in the strong magnetic field [13]. The gradient magnets can cause a lot of noise when they are rapidly turned on and off, so hearing protection is needed. The machine has a cylindrical tube where the patient lies. This area is very small and can affect people with claustrophobia. In addition, radio waves are emitted by the coils, and these are absorbed by the human body and can cause heating. MRI scanning is very delicate and the subtlest of movement can cause the image to become blurry. [15].

In conclusion, within the past century there have been many engineering advances to help improve medical care. I have only discussed three that have fascinated me but there have been countless others. Robotic surgery seems to be an exciting by-product of multiple technologies coming together. Imaging the internal structures of living bodies with sonography and MRI are wonderful examples of how raw physical phenomena can be engineered to provide critical information about disease conditions and improve cure rates.

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