THE DA VINCI SURGICAL SYSTEM: APPLICATION IN PROSTATECTOMIES AND FUTURE IN REMOTE SURGERY

Jonathan Gramley, jdg94@pitt.edu, Vidic 2:00, Johanna Siegel, jls424@pitt.edu, Vidic 2:00

Abstract—The application of the da Vinci Surgical System (DVSS) advances the fields of minimally-invasive robotic-assisted surgery and remote surgery, specifically minimizing pain, blood-loss, and opportunities for human error in the prostatectomy procedure. The DVSS is a technologically advanced surgical robot that allows a surgeon to perform an operation without actually touching the patient. In fact, the DVSS would make it possible for surgeons to interact with patients in different countries. Our paper briefly discusses the history of the DVSS, including its predecessors and the origins of robotic surgery. It also details the mechanization of the DVSS, outlining its structure and components, how it is used in long- and short-distance operations, and how it creates live 3D images. We focus primarily on the DVSS’s current application in the prostatectomy procedure and on its future in remote surgery. In addition, our paper addresses ethical concerns of the use of the DVSS, including who is to blame if an error occurs during a procedure, as well as other limitations that may keep the DVSS from being used widely.

Key Words—Endoscopic, Da Vinci Surgical System (DVSS), Prostatectomy, Minimally-invasive Surgery, Remote Surgery, Degrees of Freedom, Open Surgery

ROBOTS: THE FUTURE OF SURGERY

According to the British Medical Journal (BMJ), there were about 575,000 deaths due to medical error between the years 2000-2002, which is about 195,000 patient deaths per year [1]. For surgery specifically, every year more than 4,000 people who undergo surgery are injured from a surgical error. The consequences of these surgical mistakes include temporary injury in 59% of the cases, permanent injury in 33% of the cases, and death in 6.6% of the cases [2]. Human error is an intrinsic and inevitable part of medicine, but it can be significantly reduced through the use of new surgical technologies in robotics, such as the da Vinci Surgical System (DVSS).

Surgical procedures via the DVSS minimize human error, feature smaller incisions and scars, reduce recovery time, and decrease the chance of infection as compared with human-performed surgery. The DVSS is made up of two main parts that work in conjunction to facilitate procedures: the robot and the control console. The robot consists of four small arms used for holding tools (scissors, scalpels, etc.) and a camera that produces a live 3D image of the procedure. The control console is connected to the robot either by hardwire or remotely. At the console, the surgeon maneuvers two joysticks and two foot pedals to control the four robotic arms and make tiny incisions through which a procedure can then be carried out.

The main benefit of continuing the research on and development of the DVSS lies in its future application: remote surgery. While still a relatively new technology, the DVSS has already been successfully used in some long-distance procedures. Remote surgery is extremely useful, and even necessary in some cases. For example, if a specialized surgeon were in a different part of the world from a patient who direly needs their specialty procedure, the DVSS would allow the surgeon to perform the procedure with high accuracy from a distance. This aspect would improve and significantly advance the surgical field.

A BRIEF HISTORY OF ROBOTS IN MEDICINE

In looking towards the future of the DVSS, it is important to examine the history of this specific technology and of the field of robotic surgery as a whole. As stated in a journal article published in the Annals of Surgery, “Robots are routinely used to manufacture microprocessors used in computers, explore the deep sea, and work in hazardous environments... Robotics, however, has been slow to enter the field of medicine” [3]. As predominantly unintelligent machines, it has always been easy to program robots to do delicate or dangerous work not suitable for humans, but was never strongly considered for use in the medical field, as robots were not, until recently, well-developed enough to perform the delicate and precise procedures necessary in medicine. However, in the 1980s, a group of researchers at the National Air and Space Administration (NASA) working on virtual reality became interested in developing telepresence surgery, mainly due to the possible need for
advanced medical procedures to be performed in space. It was not until 1987 that the first minimally-invasive robotic-assisted surgical procedure was performed [3].

More recently, there have been many predecessors to the DVSS, including a robotic surgical tool called AESOP1 (Automated Endoscopic System for Optimal Positioning), developed in 1994. It was the first surgical robot arm to become FDA-approved [4]. Before the early 1990s, robotic-assisted surgery consisted of individual robotic tools, such as the Fips endoarm, that merely attached a camera to the end of a surgical tool. There were no comprehensive manipulation support systems for surgeons using robotic surgical devices, a shortcoming which resulted in many limitations in dexterity. Then, in the 1990s, a move was made to solve this problem with the introduction of the concept of a “master-slave telemanipulator.” This was the concept that surgeons could manipulate a system of instruments at the same time while operating from a master console [4]. The DVSS falls under this category of “master-slave telemanipulator,” and its widespread use has allowed surgeons many more degrees of freedom in their hand movements. In 2000, the DVSS became the first robotic system cleared by the FDA [5]. The following section will detail the complicated process of communication between the manipulation console and the surgical tools as well as describe the structure of the DVSS.

MECHANIZATION: HOW DOES THE DVSS ACTUALLY WORK?

In order to promote the concept of minimally-invasive endoscopic surgery, the DVSS is made up of a control console and a robot with four mechanical arms to make small incisions that minimize blood loss, scarring, and recovery time of the patient. An operating room (OR) that incorporates the DVSS looks and operates differently from a traditional OR.

As shown in Figure 1, the patient is on an operating table in the center of the OR with the hard-wired control console just a few feet away. The trained surgeon operates from the control console while OR assistants, nurses, and an anesthesiologist (seen around the operating table) change the tools in the DVSS and monitor the patient’s vitals. Every aspect of the DVSS, including the console controls and the arms, is in the control of the surgeon operating the machine.

The Console

In order to operate the surgical robot, a trained surgeon sits at a control console that is usually located in the same room as the patient who is being operated on. The console consists of two handles and two foot pedals that directly control the four arms of the robot. It also has two eyeholes that allow the doctor to view a three-dimensional image of the procedure, as if it were open surgery. The 3D image is in high definition and the image can be magnified up to ten times the original without losing quality. The console has a touchpad that allows the surgeon to control the audio and visual settings of the robot manually to his or her preference.

Along with audio and visual preferences, the console features four different ergonomic settings for added comfort for the surgeon during surgical procedures. The two handles have small fingertip controllers attached for even more precise movement in the procedure. The foot pedals mainly serve to swap between instruments fluidly during surgery. The control console is also able to be paired with another console to create a dual console system that allows for an effective training mechanism. An untrained surgeon can work alongside a trained professional to improve his or her proficiency with the DVSS [6].

The Arms

The patient side cart is where the four arms of the DVSS robot are, pictured in Figure 2.
The arms of the DVSS have seven degrees of freedom, which include the ability to pivot and rotate at both bases of the arms, and the ability to bend at the joints of the arms. Figure 3 labels each degree of freedom with a theta (θ).

These degrees of freedom give the arms the qualities of a human hand, as each arm possesses the same number of degrees of freedom as a human hand. Each arm comes equipped with a variety of attachments. Arguably the most notable attachment is a camera that captures and projects a live 3D image of the procedure to the doctor operating at the control console. In order to keep consistent with the DVSS’s claim to minimally invasive surgery, all of the attachments are small enough to fit through the small incisions made by the robot during the procedure. Just because the instruments are miniaturized, however, does not make them any less effective. The DVSS is compatible with a multitude of instrument attachments, including forceps, needle drivers, retractors, and tools for specialized procedures in which precision is paramount. The arms of the DVSS have much more flexibility than a human hand, and they increase the extent of all seven degrees of freedom of the human hand, more flexibility than is commonly displayed by similar robotic arms. As a result, the arms can be easily maneuvered once the incisions have been made so as to access all areas of the body needed for the procedure. The use of a robotic arm can also minimize the effect of human error, since it is more stable and less likely to get fatigued than a human hand is [9].

**Short Distance Operations**

In the most common DVSS procedures, the control console and the robot are in the same room or in adjoining rooms. Communication between the two components occurs through a two-way connection of signals. The first part of the connection occurs when the surgeon at the control console maneuvers one or more of the handles or foot pedals, corresponding to a certain arm on the robot. This motion is then converted into an electrical signal that is passed on to the mechanical arms. When the arms receive the electrical command, they act according to the intentions of the surgeon. Simultaneously, the robot is sending signals to the control console as feedback for the surgeon [10].

**Long Distance Operations**

Due to the remote connection between the DVSS’s console and robotic arms, it is possible to operate on a patient from any distance. The remote connection is made possible through complex remote communication and electrical connection. The data signals used in DVSS long-distance procedures are transmitted via asynchronous transfer mode (ATM). This is a process of splitting data into packets of fixed size and routing them to a fixed destination. ATM is not necessarily more effective than other data transfer methods such as Ethernet or Internet, but it is more guaranteed. It is far more complex than most data transfer methods, making it less commonly used. This leads to less “data traffic” and subsequently a more stable and guaranteed data transfer rate, which is essential in remote surgery [10].

**Training**

As with any new technology, the question that arises is how are people going to learn how to use it? The DVSS is a non-traditional surgical tool, and therefore there are a few non-traditional answers to this question. Multiple training modules currently exist, and more are being developed, for surgeons wanting to use the DVSS. One such module is a virtual reality trainer used to simulate the use of the DVSS during multiple types of procedures [8]. Another such training device is called the dV-Trainer [11], developed specifically for the DVSS. It includes training modules for suturing and knot tying, needle control, troubleshooting, and camera use. The existence of these training modules decrease significantly the time it takes for an expert surgeon to be fully trained on the use of the DVSS and therefore make the DVSS a safer tool.

**PRIMARY USES OF THE DVSS**

Robotic-assisted surgeries have become more common due to the increasing awareness of the benefits they provide for patients. Since the development of the DVSS, robotic surgery has replaced many traditional open surgeries for prostatectomies (removal of the prostate gland), nephrectomies (removal of one or both kidneys), and hysterectomies (removal of the uterus) [12]. In addition, it is extremely common to use the DVSS in many cardiac surgeries including mitral valve surgery, atrial fibrillation surgery, and coronary artery bypass grafting [13].
Application to the Prostatectomy Procedure

One of the most common procedures that the DVSS is used for is the prostatectomy procedure. Prostatectomies are performed as a type of treatment for prostate cancer. As stated by Dr. Michael Palese, a urological surgeon and the Director of Minimally Invasive Urology at Mount Sinai Hospital in New York City, “[robotic surgery is] also great for prostate surgery because you can see really well while operating because of the magnification” [12].

As shown in Figure 4, during DVSS-assisted prostatectomy procedures, the patient is operated on through three to six keyhole incisions of 3-12mm in length, instead of through an incision of 10-40cm over the thoracic or abdominal cavity [4]. As less sub-dermal flesh is exposed to the air, there is less risk for infection when a patient is operated on using the DVSS versus when the patient undergoes traditional surgery. In addition, less scarring occurs due to the smaller incisions.

As of now, prostatectomies via the DVSS are just as effective as traditional open surgery. In a study done by the Prostate Cancer Foundation, 308 randomly assigned men were studied to see how they did in terms of their urinary and sexual function at six weeks and twelve weeks after their surgery (either robotic or open). The study found that there were no significant short-term differences in their urinary or sexual function depending on the type of surgery received. However, says Dr. Stacy Loeb, assistant professor of urology and population health at New York University, “This paper reports the very early outcomes from a small, randomized trial… Although a comparison of the immediate postoperative outcomes is interesting, what is much more important are long-term functional outcomes of these procedures, and how well they controlled the cancer” [15].

Based on Dr. Loeb’s commentary, it is currently impossible to say whether the DVSS will be just as effective as open surgery in the long term. Therefore, it will be necessary for additional studies to be conducted that evaluate the urinary and sexual health of prostatectomy patients farther into the future.

Other Procedures

Since the DVSS has the ability to interchange surgical tools, it ends up being a very multifunctional device with diverse uses. Dr. Palese, urological surgeon at Mount Sinai Hospital, also performs nephrectomies with the DVSS. He says that, “with kidney surgery, you used to have to make larger incisions and maybe even remove part of the rib cage. With the robot, that's no longer the case” [4]. Less removal of body parts lessens the risk for postoperative complications.

The DVSS is also widely used in the gynecologic field. A recent study based on a survey given to 6,262 women who received hysterectomies at the Newark Beth Israel Medical Center found that the women who received robotic hysterectomies reported significantly higher overall satisfaction, were more likely to recommend the approach to others, and more likely to choose robotic-assisted surgery again [5]. This study provides some justification for the continuation of use and improvement of the DVSS and other similar robotic systems. Further justification can be found in the fact that between 2001 and 2013, rates of open surgery for hysterectomies decreased by 64 percent. During the same period, robotic-assisted surgery rates rose from zero use to more than one-third of all hysterectomies performed [5].

It is clear to see that the DVSS, and robotic surgical devices in general, are becoming more and more integral to most surgeries and will be an extremely applicable technology in the very near future. It is therefore warranted to continue to do research on the effectiveness of these machines and perform more experiments to improve their safety and quality.

FUTURE OF REMOTE SURGERY

The outlook on the future of remote surgery, and on the DVSS in particular, is favorable and rich in possibilities. Long-distance robotic surgery is needed in today’s world. Over 1,000 endoscopic operations have already been completed successfully with the DVSS. Moreover, the type and number of procedures performed, along with the number of robotic surgery systems installed in hospitals all over the world, will increase in the coming years. Currently, over 50 systems are used routinely in the United States, Europe, and Japan [4].

Experimentation in remote surgery has been prevalent for more than a decade, and the progression of this idea is far from over. According to the American Society of Mechanical Engineers (ASME), “Remote presence robots bring big-city know-how to small-town clinics and trauma centers” [16]. The application of the DVSS to remote
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surgery can bring specialists from around the world to a patient who otherwise would not have the opportunity to receive surgery. Distance barriers for patients who desperately need a specific operation would be removed since specialized care could be brought to them remotely. In addition, the DVSS would also allow surgeons to perform basic medical procedures, such as prostatectomies, on patients in small towns without access to medical care beyond that administered by a general practitioner.

The DVSS could also serve as an invaluable training tool for new surgeons. Medical students as well as surgeons just entering the field would have the opportunity to ask for help from more experienced surgeons, which would multiply the effectiveness of the most expert surgeons globally, truly making the DVSS a socially sustainable tool.

Social sustainability, as described by Western Australia Council of Social Services (WACOSS), “occurs when the formal and informal processes; systems; structures; and relationships actively support the capacity of current and future generations to create healthy and livable communities” [17]. By spreading the effectiveness of expert surgeons, the DVSS proves to be creating “healthy and livable communities” by making advanced medical care a widely-accessible service.

Since the first successful robotic surgery across the ocean in 2001 (from France to New York, dubbed the Lindbergh Operation), the quality of robotic surgery has improved vastly. Robotic surgery, which currently uses remote communication, is close to taking the next step to long-distance remote surgery. Once this step has been taken, the possibilities are endless. Specifically, NASA has expressed interest in remote surgery in order to operate on astronauts from the Earth. Also, the US Army contracted the development of the prototype of the DVSS in order to utilize remote surgery on the front lines to protect the medics enlisted in the Army [6]. Overall, the development of remote surgery would improve the odds of all those without regular access to top-of-the-line surgeons.

TECHNICAL LIMITATIONS OF THE DVSS

As with any new technology, the DVSS comes with a multitude of issues and concerns. Most of these matters regard ethics, responsibility, and malfunctions, as well concerns about training, cost, efficacy, and safety. The next few sections go in depth into these concerns, addressing them and suggesting ways to fix major issues.

Feedback Concerns

One of the most important aspects in performing a surgery is that the surgeon receives haptic information back from whatever part of the body he or she is operating on. When a robotic arm is used, however, the surgeon experiences a lack of tactile feedback from the patient’s body. So, although the DVSS improves dexterity and increases exposure to hard-to-reach anatomy, the lack of tactile tissue feedback makes robotic-assisted surgery very different from open surgery; the surgeon is not able to detect how hard or soft they are using each instrument [13]. Therefore, more work will need to be done in this regard in order to make robotic surgery a safer option.

Better Late Than Never?

In terms of limitations cased by mechanical failures, one concern is latency, or the delay between the initiation and completion of transferring data. In any remote connection, be it between two cell phones, a computer and the internet, or a TV dish and a satellite, latency is an issue. However, the latency in these examples does not have as grave of consequences as it does in remote surgery. Remote surgery is aptly named because it is remote, which means that in communicating wirelessly with the robot, there may be delays, if only for a millisecond.

Most of the latency is attributable to the time it takes to convert images and commands inputted by the surgeon into electrical signals. However, a small portion of this latency is also attributed to the time that the electrical signal is traveling between the two components and is directly proportional to the distance between the robot and the console. This is the main reason operating over a distance is difficult to accomplish. In terms of operating on astronauts in space, data does not yet exist as to what the latency of the DVSS would be. However, with future studies, it is possible that this question may soon be answered.

The main step to reducing the latency will be to improve the connection between the components of the DVSS in order to increase the traveling velocity of the electrical signals, and to reduce the conversion time from images or gestures to transmittable electrical signals. Although the average latency of the DVSS over a round trip distance of about 14,000 km is only 155 milliseconds [10], any delay in a medical procedure can be the difference between life and death for a patient, and is a key reason that the DVSS has not yet made the complete jump to long-distance surgery. Once this delay is corrected, however, and procedures are able to happen over distance in as close to real time as possible, the future prospects for remote surgery will be endless.

If the DVSS is to be used to perform medical procedures in developing countries and become a truly socially sustainable tool, the lack of reliable ATM connection would need to be addressed and lag time would need to be analyzed to determine the potential effects of long distance remote surgery across the world.

Surgery Hackers

Another concern with any technology operating over a network is the potential for it to be hacked. In a controlled study conducted at the University of Washington,
researchers found that by hacking the router that connected the control console to the robot, they were able to change the commands so that the robot’s motions were jerky and erratic. In addition, they were able to make the movements initiated by the surgeon longer or shorter than intended and were even able to trigger an automatic stop that prevented the operation from being continued. The researchers also found that the 3D video connection produced by the robot was publically accessible [18], breaching patient privacy.

Cyber hacks are a particular concern for this technology if it is to be used in the context of surgery on the battlefield. Any attack at a crucial moment could be lethal for the patient. However, researchers are currently working on some techniques to minimize cyber attacks by encrypting the data transferred from the console to the robot, making the software more sensitive to errors and attempted data changes, and better monitoring the network status before and during the surgery [18].

**ETHICS AND SOCIAL IMPACT OF THE DVSS**

**A Paradigm Shift**

Robotic surgery has taken over many surgical fields so much so that it has caused somewhat of a paradigm shift in medicine. It has been noted by many clinicians that “younger surgeons who have more experience with video games picked it [robotic surgery] up quicker than older surgeons” [12]. While this is an advantage to younger surgeons, the increase in dependence on robotic surgical tools has caused “some amazing surgeons [to] almost lose their practices overnight because they weren't able to transition fast enough and adapt to the new technology,” says Dr. Palese of Mount Sinai Hospital [12]. This may signify that the DVSS is not very socially sustainable in some ways. Based on the definition of social sustainability previously stated, if the DVSS creates healthy and livable communities for everyone it affects, it would be classified as socially sustainable. However, although the DVSS may better the lives of, and prove to be socially sustainable for the patients on which it operates, it may make the lives of older, more experienced surgeons more difficult. In order for it to be completely socially sustainable, the DVSS must be beneficial, or at least not detrimental, to the surgeons who use it.

One way in which the DVSS may become more socially sustainable in the future is for more training programs, geared specifically towards older surgeons for whom the DVSS may be less intuitive. This would level the playing field in terms of competition between older and newer surgeons.

Another shift in the medical field that may occur if robotic surgery becomes widely implemented is that young surgeons may be exposed to robotic surgery very early on in their surgical careers and may not pick up the basic open surgery skills crucial to any successful surgeon. Currently, if the DVSS is to be used over long distances, a highly-trained surgeon is needed in the operating room with the patient in case of an unforeseen error, malfunction, or patient issue. If that surgeon does not know basic open surgery procedures, the patient’s life could be at risk. So, while the DVSS should be widely implemented as it is a state-of-the-art surgical tool, measures should be taken to make sure that new surgeons are trained in open surgery techniques as well as the newer robotic surgery techniques.

**Ethical Concerns**

With new forms of medical procedures come new forms of ethical concerns. Namely, who is to blame in the event of an accident? Is it the machine that malfunctioned, placing the blame on developers of the robot? Or is it directed toward the surgeon using robot and the hospital under which they are employed? Who is responsible for paying damages, if any?

One court case centered on a DVSS surgery attempted to answer these questions. This case concerned a prostatectomy carried out at Bryn Mawr Hospital in Philadelphia, Pennsylvania, in 2005, on a patient called Roland Mracek. According to the reports, in 2004, Mracek underwent a prostate biopsy that showed evidence for a prostate adenocarcinoma. A few months later, the Hospital surgeon informed Mracek that a Da Vinci robot would be used to carry out radical prostatectomy in order to minimize the risk of erectile dysfunction. This surgery took place in 2005. During the robot-assisted intervention the DVSS started displaying error messages. About 45 minutes elapsed between the moment in which the surgeons decided to stop using the robot and the moment in which they were able to go on manually. One week after the intervention, Mracek suffered of a serious hemorrhage; he now suffers from total erectile dysfunction and daily abdominal pains [19].

From this case raises the question of who, if anyone, is to absorb the blame for Mracek’s new health condition? The court decided that Mracek did not submit enough evidence to say definitively that it was the machine’s error messages that caused his new condition. This case is important in that it opens new doors for potential legal issues brought to light due to the increase in use of machines and robotic assistants for surgeries.

**Financial Concerns and Sustainability**

The DVSS is still relatively new and, as with any new product, it is very expensive. On average, the DVSS robot costs between $1.5-2 million for a hospital to purchase, not including training programs for the surgeons. In addition to the purchase price, the system has an annual service contract that costs between $100,000 and $170,000 [20]. “To make
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buying a da Vinci financially viable, hospitals generally need to perform 150 to 300 procedures annually for six years to offset the upfront and ongoing costs of acquiring it,” says Vijay Kumar, associate managing director for the ISI Group, an investment banking company [20]. Most of the instruments used by the DVSS can cost $2,300 and are only good for ten uses. In addition, the lifetime of a DVSS generally has a maximum of seven years, causing hospitals to need to purchase a new machine after it is no longer useful [21]. However, the DVSS is a powerful marketing tool for hospitals, as patients may choose a hospital with a da Vinci system based on the perception that it is a state-of-the-art facility, and drawing more patients is always good for a hospital.

Financial sustainability refers to operations from which an organization is able to make a profit. It is ultimately up to the hospital to determine whether the DVSS is worth the investment and is a financially sustainable acquisition for them based on the factors mentioned above, as well as many others. In order to become more financially (and environmentally) sustainable, tools should be developed that are good for more than ten years and machines that are good for more than seven years. This will require research into latency causes, new materials, and better computers, however with DVSS-assisted surgeries gaining popularity, these issues may be solved in the near future.

An ethics issue related to financial sustainability is that the DVSS can only bring the expertise of well-established surgeons to small town hospitals via telepresence surgery if the small town hospital decides that the DVSS is a financially sustainable tool. Otherwise, expert doctors may be driven to hospitals offering DVSS remote surgery and people living in the small towns will not have access to anything above basic medical care. Is it for the use of the DVSS to become the norm, if small-town hospitals cannot purchase it?

Another aspect of financial sustainability is the cost of robotic surgery to patients. In terms of cost to patients, DVSS procedures cost $2,000 more than a normal procedure [20]. However, since procedures performed using the DVSS have extensive benefits, it may be argued that this is a situation in which you ultimately get what you pay for. With the increase in production and widespread use of the DVSS, these prices will decrease, making surgeries with smaller incisions and scars, less recovery time, and lesser chance of infection available to more patients.

THE DVSS: A SURGICAL LONG DISTANCE RELATIONSHIP

Robotic surgeries performed with the DVSS have the potential to completely revolutionize the surgical field. With decreased risk of infection and scarring, decreased recovery time, and minimization of human error, surgery by DVSS has become a popular option for many hospitals and patients. The DVSS has been used most commonly in the prostatectomy procedure, as well as in hysterectomies and nephrectomies.

There are, however, certain limitations that cause the DVSS to not be a feasible option for patients and hospitals, including cost and several ethical concerns. It will be important for these limitations to be addressed and hopefully minimized before widespread use of the DVSS is achieved.

Aside from current uses and limitations, however, lies the astonishing and possibly the most exciting feature of the DVSS: its ability to be used over long distances for remote surgeries. Remote surgery opens up so many new prospects, including surgery in space and the maximization of a skilled and expert surgeon’s influence, that it seems almost foolish not to continue to modify and develop the DVSS to achieve extensive remote use.

**SOURCES**


ADDITIONAL SOURCES


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