3 History of Robotic Surgery

Farid Gharagozloo, Barbara Tempesta, Mark Meyer, Duy Nguyen, Stephan Gruessner, and Jay Redan

3.1 Background

Robots have fascinated and preoccupied human minds for centuries—from ancient tales of "stone golems" to modern science fiction [1].

The concept of autonomously operating machines goes back as early as 1400 BC when Babylonians developed a clock that measured time using the flow of water. This was the first automatic device in history.

In 400 BC, Archytas of Tarentum, considered the father of mathematical mechanics, developed a steam-powered autonomous flying machine. [2] The wooden structure was based on the anatomy of a pigeon and contained an airtight boiler for the production of steam. The steam's pressure would eventually exceed the resistance of the structure, allowing the robotic bird to take flight.

F. Gharagozloo (✉)
Professor of Surgery, University of Central Florida, Surgeon-in-Chief, Center for Advanced Thoracic Surgery, Director of Cardiothoracic Surgery, Global Robotics Institute, Director of Cardiothoracic Surgery, Advent Health Celebration, President, Society of Robotic Surgery, Director, International Society of Minimally Invasive Cardiothoracic Surgery, Celebration, FL, USA
e-mail: Farid.Gharagozloo.MD@adventhealth.com

B. Tempesta
Center for Advanced Thoracic Surgery, Global Robotics Institute, Advent Health Celebration, Celebration, FL, USA

M. Meyer
Department of Surgery, Wellington Regional Medical Center, Wellington, FL, USA

D. Nguyen
Global Robotics Institute, Advent Health Celebration, Celebration, FL, USA

S. Gruessner
Department of Surgery, University of Illinois at Chicago, Chicago, IL, USA

Formerly of Global Robotics Institute, Advent Health Celebration, Celebration, FL, USA

J. Redan
Advent Health Celebration, Celebration, FL, USA

In 322 BC, the Greek philosopher Aristotle was one of the first great thinkers to consider automated tools and suggested the manner in which these tools would affect society at large. He imagined the great utility of robots, writing, "If every tool, when ordered, or even of its own accord, could do the work that befits it … then there would be no need either of apprentices for the master workers or of slaves for the lords."

In 250 BC, Ctesibius created a clepsydra, or water clock, which included a number of elaborate automatons. Ctesibius' design allowed for the dropping of pebbles onto a loud gong, effectively making it the first alarm clock as well as an example of early automaton design.

During the same period in the third century BC, the Chinese built a singing dancing robot out of wood and leather for the entertainment of King Mu of Zhou [3, 4].

In the eleventh century, during the dark ages in Europe and the Golden Age of Islam, Arab Muslim polymath Badi'al-Zaman Abū al-'Izz ibn Ismā'īl ibn al-Razāz al-Jazari, an engineer and mathematician who is considered by many to be the father of robotics, devised segmental gears [5]. Many of his robotic creations were powered by water and included everything from automatic doors to a humanoid autonomous waitress who could refill drinks. al-Jazari constructed multiple automations including a floating mechanical music-playing band that was programmable using a rotor with moveable peg cams.

In 1478, Leonardo DaVinci invented a small carriage which was powered by flexible bows and had pegs that could be inserted into a wheel to create a pre-set steering path. This was the first motorized vehicle, and one of the first programmable devices.

DaVinci was influenced by al-Jazari's work, and later in 1495 went on to invent the first autonomous machine modeled after the human figure (therefore the inspiration for the "da Vinci" robotic surgical system!). With the use of a series of pulleys and gears, Leonardo DaVinci's metal-plated warrior could mimic human movements of the jaw, arms, and neck [6].

In 1530, the German mathematician Johannes Müller von Königsberg created a mechanical eagle.

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In 1540, Giannello Torriano designed a female figure which could play the mandolin [7].

Circa 1600, Japanese invented Karakuri Ningyo, a small human-shaped wooden robot which was driven with a series of gears.

The seventeenth century saw the invention of "Machine Control" using centrifugal ball governors. Centrifugal governors (ball governor) were used to regulate the speed of grindstones in windmills. This device was later employed in James Watt's steam engines. The word "governor" is derived from the Ancient Greek κ[kappa]υ[upsilon]β[beta]ε[epsilon]ρ[rho]ν[nu]ή[eta]τ[tau]η[eta]ς[sigma] (kybernētēs), meaning "steersman, pilot, or rudder." The ball governor is a feedback device; its output is fed back into the device as its input [8]. An additional landmark invention which influenced the design of robots was the "Pendulum Clock" in 1656. It employed the verge escapement mechanism with a foliot or balance wheel timekeeper and a series of gears. It became the standard timekeeping device in the latter half of the seventeenth century.

In 1737, Jacques de Vaucanson created a clockwork "Duck" capable of flapping its wings, quacking, and eating food with the illusion of digestion. His other invention was "The Flute Player"—a life-sized humanoid automaton that could play up to 12 different songs on the flute [9]. The automaton used a series of bellows to "breathe" and had a moving mouth and tongue that could vary the airflow, allowing it to play the instrument [9].

In 1769, Hungarian inventor Wolfgang von Kempelen built "The Turk," a clockwork-filled box with a middle eastern-looking figure, protruding from the back. The device gained fame as an automaton capable of playing chess against skilled opponents, but in reality, the clockwork was set dressing, and the only functional part was a concealed dwarf chess master turned puppeteer.

In 1772, Pierre Jaquet-Droz devised androids, the "automata," that could write letters, play a musical box, and draw pictures with the use of interchangeable programmable wheels [10, 11].

In 1800, Alessandro Volta invented the first chemical battery. This was significant for the future development of robotics.

In 1801, French silk weaver and inventor Joseph Marie Jacquard invented an automated loom controlled by punch cards.

In 1835, Joseph Henry invented the electrical relay, by which a current could activate a switch. Originally used for signal amplification on telegraph lines, it was eventually used in machine control systems and logic circuits.

In 1846, Austrian mathematician and inventor, Joseph Faber, created Euphonia, a speaking, singing robot [11]. The machine featured a humanoid feminine face connected to a keyboard, where the face's lips, jaw, and tongue could be controlled. A bellows and ivory reed provided the machine's voice, and pitch and accent could be altered through a screw in the face's nose.

In 1863, the term "android" was first used in U.S. patents in reference to human-like miniature mechanical toys. Later in 1886, "Android" was cited in fiction. "L'Ève future" or "The Future Eve," was a Symbolist science fiction novel by the French author Auguste Villiers de l'Isle-Adam, featured an artificial woman, created by Thomas Edison that lacked a real woman's flaws.

In 1893, Canadian George Moore built a life-sized steam-powered man. It walked at the end of a rotating boom at a speed of around nine miles per hour.

In 1907, Tik-Tok, the first true robot in fiction, made its first appearance in Ozma of Oz.

In 1912, Leonardo Torres y Quevedo, made "The Chess Player." The device was capable of playing chess against a human opponent and featured an electrical circuit and a system of magnets which moved the pieces. It debuted at the 1914 World's Fair in Paris to great excitement and acclaim.

The term robot was introduced in the play Rossumovi Univerzální Roboti (R.U.R) by the Czech playwright Karel Čapek in 1923 [12]. The Czech word "robata" means "drudgery." In the play, robots—mechanical objects designed for drudgery—take over the human race.

In 1926, Film director Fritz Lang released *Metropolis*, a silent film set in a futuristic urban dystopia. It featured a female robot—the first to appear on the silver screen—that took the shape of a human woman in order to destroy a labor movement.

In 1928, British engineer, Alan Reffell, and World War I veteran Captain William Richards created "Eric." "Eric," which was operated by two people, could move its head and arms, and could speak via a live radio signal. Eric's movements were controlled by a series of gears, ropes, and pulleys and the robot reportedly spat sparks from its mouth. As an homage to the Čapek's 1921 play R.U.R, Eric had the letters R.U.R. engraved into its chest.

In 1929, Japanese biologist Makoto Nishimura made the robot Gakutensoku. It was over seven feet tall, could change its facial expressions through the movement of gears and springs in its head and could write Chinese characters.

In 1942, Issac Asimov first used the term "robotics" in his books *Runaround* and outlined the three laws of robotics: that robots must not harm humans, that they must obey orders from humans, and that they must protect themselves from threats provided their self-preservation doesn't break either of the first two laws [13, 14].

In 1947, the science of Cybernetics emerged. A congress on harmonic analysis was held in Nancy, France, and was attended by Mathematician Norbert Wiener, who would be inspired to write the 1948 book *Cybernetics, or Control and Communication in the Animal and Machine*. This new science was concerned with feedback control systems in machines and nature. The word "cybernetics" is derived from the Ancient Greek κ[kappa]υ[upsilon]β[beta]ε[epsilon]ρ[rho]ν[nu]ή[eta]τ[tau]η[eta]ς[sigma] (kybernētēs), meaning "steersman, pilot, or rudder." The ball governor, invented in the seventh century, is recognized as a cybernetic device for its use of feedback in control of machinery.

During the remaining decades of the twentieth century, the notion of robots was an enormously popular theme for works of science fiction. In films, plays, literature, and television; robots range from friendly companions, to vicious predators which were manipulated by villains, to autonomously functioning machines rising against humanity.

In 1961, the first industrial robot, the Unimate, was developed by Unimation Inc. The Unimate robotic arm was first installed at the General Motors assembly line in Ewing, New Jersey, and was capable of transporting die-cast parts and welding them into place. This device would soon change the face of the manufacturing industry forever.

In 1968, MIT's Marvin Minsky created the "tentacle arm"—a robotic 12-jointed arm that was powered by hydraulics and could be controlled via a joystick.

In 1969, Victor Scheinman created the Stanford Arm, a robotic arm that is considered to be one of the first robots to be controlled exclusively from a computer.

The early 1970s saw the unveiling of the world's first full-scale anthropomorphic robot—the WABOT-1 which was created by Ichiro Kato in Tokyo's Waseda University.

The 1970s also saw the progression of industrial robotics when, in 1973, German company KUKA released the FAMULUS—the first industrial robot with six electromechanically driven axes.

In 1976, two robots, Viking 1 and Viking 2, that were powered by radioisotope thermoelectric generators landed on Mars.

In reality and in practical daily life, robots have revolutionized industrial production from automobiles to computer chip production to pharmaceutical manufacturing. Industrial robots are used to accomplish repetitive tasks precisely without fatigue. Unlike robots of science fiction, these robots are driven by computers that are in turn programed for specific tasks. Consequently, to the lay public robots are either a science fiction curiosity or mechanical machines that are driven by digital systems without human intervention.

When referring to surgical robots, the popular notion of robots can be a cause for great fear. It is therefore somewhat unfortunate that surgical instruments that are manipulated from a remote console and represent extensions of the surgeon's mind and hands are referred to as "robots." Consequently, it is crucial to alleviate any misgivings in the patient population about the nature of surgical robots. In the future, surgical robots may be directed from vastly remote locations and may even have computer-controlled or autonomous function. However, presently, surgical robots are mere instruments that are remotely manipulated by a surgeon using an electromechanical interface. Present-day surgical robots are not autonomous nor are they driven by preprogrammed computers.

3.1.1 Video-Endoscopic Surgery

Video surgery came about as a direct result of development of the cystoscope. In 1806, Philip Bozzini of Frankfurt Germany developed the first known endoscopic instrument the "Lichtleiter." [15] It had an eyepiece and a speculum which was introduced into the body cavity. Illumination was provided by a candle which was placed in a container located between the eyepiece and the speculum. As the candle was interposed between the observer's eye and the body cavity, all that the observer saw was the light of the candle! The instrument was used to examine the vulva, the rectum, urethra, and upper respiratory passages. However, as it illuminated a small area and resulted in considerable pain, the instrument was denounced by the Faculty of Medicine in Vienna, Austria [16]. In 1827, Pierre Segala of France devised a similar instrument that used mirrors to deflect the candle light from the observer's eye [17]. In 1828, John Dix Fisher of Boston described a similar endoscope in the United States [18]. In 1853, Antoin Desormeaux, considered by some as the "father of endoscopy," devised brighter illumination by the use of alcohol and turpentine and a Plano convective focusing lens [19]. In 1877, Max Nitze incorporated the revolutionary concept of distal illumination using a heated platinum filament and devised the forerunner of the modern cystoscope [20]. In 1883, David Newman of Glasgow, UK, incorporated an incandescent lamp into the cystoscope [21]. Soon thereafter, Charles Preston of Rochester, New York, developed a "cold" low amperage lamp that did not require a cooling system and interestingly was used in endoscopes for over 100 years until the advent of Fiberoptics [22].

Early in the twentieth century, gynecologists and surgeons began to evaluate the abdominal and thoracic cavities using endoscopes. The invention of the automatic insufflator gave rise to the era of laparoscopic surgery. In 1966, Kurt Semm was the first to perform laparoscopic gynecologic procedures [23].

During the 1970s and 1980s, laparoscopy was applied to the diagnosis and staging of pathologic processes in the abdomen. The German surgeon Erich Muhe, in 1985, the French surgeon Philippe Mouret, in 1987, and Americans McKernan and Saye, in 1988, independently performed the first laparoscopic cholecystectomy procedures [24]. Interestingly, by 1990, laparoscopic cholecystectomy had become the standard of care [25]. Following the advances in the use of minimally invasive surgery in the abdomen in the

1980s, video-assisted thoracic surgery (VATS) was born in the 1990s.

Although presently video-assisted techniques occupy a significant role in the armamentarium of virtually all surgical subspecialties, the advanced videoendoscopic procedures have not been readily embraced. Most advanced videoendoscopic techniques require precise dissection, manipulation of delicate structures, endoscopic suturing, and three-dimensional visualization. The current video endoscopic technology has the following limitations:

- The 2D camera system causes impaired visualization. Furthermore, video cameras are manipulated by an assistant and not the surgeon. As a result, the rapid adjustment of the visual field, which is necessary for complex surgical procedures, is not possible.
- Instruments are very long and operate on a fixed fulcrum at the point of entry of the trocar. This results in limited range of motion, diminished tactile feel, and exaggeration of the surgeon's natural tremor. As a direct result of pivoting far away from the operative site, the conventional endoscopic instruments have restricted access to non-contiguous structures and reverse or counterintuitive response at the instrument tip in relation to the movements of the surgeon's hands. Suturing and not tying is difficult. Appropriate attention is difficult to achieve when Endo corporeal knots are tied by instruments that have a fulcrum point at the trocar site rather than the target tissue. Furthermore, long length of the instruments compromises ergonomics and thereby contributes significantly to surgeon fatigue and longer learning curves.

In the 1990s, it was clear that computer-enhanced instrumentation had the potential of solving limitation of conventional video endoscopic techniques.

3.2 Robotics in Medicine

3.2.1 PUMA (Programmable Universal Manipulation Arm) 560

In 1978, Victor Scheinmann while working at Unimation, the company that produced the first industrial robot, developed PUMA. The PUMA 560 had six degrees of freedom [26].

The first documented use of a robot-assisted surgical procedure occurred in1985 when the PUMA 560 robotic surgical arm was used to orient a needle for a brain biopsy while under computer tomography (CT) guidance during a neurosurgical biopsy.

3.2.2 PROBOT

In the late 1980s, PROBOT robotic system was designed at Imperial College London in order to assist in transurethral prostatectomy [27]. PROBOT had four axes of movement, a 40,000-rpm rotating blade for resection, and a compact size. Using a computer-generated 3D model of the prostate, the surgeon could outline a specific area for resection. In turn, PROBOT calculated the trajectories of excision, and the procedure was executed by using a computer-generated 3D model of the prostate.

3.2.3 ROBODOC

The first computer-enhanced surgical instrument was the ROBODOC (Integrated Surgical Systems, Sacramento, CA, USA).

IBM's Thomas J. Watson Research Center and researchers at the University of California, Davis, began collaborative development of an innovative system for Total Hip Arthroplasty (THA). Their goal was to create a robotic surgical system that would redefine precision in joint replacement procedures. ROBODOC enabled precise drilling of the shaft of the femur by orthopedic surgeons. ROBODOC was first used clinically in 1992 [28, 29].

3.2.4 Aesop

Aesop (automated endoscopic system for operative positioning) (Computer Motion Inc., Santa Barbara, California) was introduced in 1994. Computer Motion was funded by NASA with the goal of creating a robotic arm to be used in space. Instead, a version of the arm found its way into surgical use as a table-mounted laparoscopic camera holder. Aesop gave the surgeon control of the video endoscope. It provided a stable field of vision and was directed by voice commands from the surgeon [30–34].

3.2.5 Zeus

The Zeus robotic surgical system (Computer Motion, Santa Barbara, California) was introduced in 1998. The Zeus system is no longer available for clinical use.

The Zeus and the da Vinci robotic surgical systems were conceptually similar. They both had a surgeon console connected by an electronic interface to robotic arms that were driven by cables and were used to manipulate the video endoscope and the surgical instruments. The Zeus system had an open workstation that gave the surgeon direct external view of the operating room. The Zeus system used a traditional monitor with a computer simulated three-dimensional visualization system using special glasses. The Zeus arms consisted of three separate working arms (three ESOPs) that were independently fixed to the operating room table. The Zeus arms had 5° of freedom.

ZEUS made its most prominent mark in cardiac surgery. A Canadian study demonstrated ZEUS's technical ability by successfully harvesting the left internal mammary arteries, using a three-trocar technique, in 19 patients who all subsequently had excellent clinical outcomes [35, 36]. Further studies showed ZEUS' ability to successfully assist in the anastomoses of closed chest, on-pump and off-pump coronary artery bypass grafting [37]. ZEUS was also capable of long-range telepresence surgery. Using a fiber-optic cable running from the ZEUS console in New York, USA, to the robot operating on the patient in Strasbourg, France, Marescaux successfully performed a telerobotic cholecystectomy in 2001 [38].

3.2.6 da Vinci

The da Vinci robotic surgical system (intuitive surgical, Sunnyvale California) was introduced in 1997 (Figs. 3.1, 3.2, and 3.3). The da Vinci system used endowrists with 6° of freedom, with both pitch and yaw, which gave 360° rotation of the instrument dress. In the da Vinci system, the four robotic arms were mounted onto a cart, which was wheeled onto the operating table. The original da Vinci system (standard) was improved with the introduction of the da Vinci S, da Vinci SI, da Vinci XI systems (Figs. 3.4, 3.5, 3.6, 3.7, and 3.8).

The da Vinci robotic surgical system was the product of research performed by SRI (Stanford Research international). In 1990, SRI received funding from the National Institutes of Health in order to develop a prototype robotic surgical system in conjunction with the Defense Advanced Research Projects Agency (DARPA). Using a telepresence surgery system created by Phil Green, Richard Satava, Joe Rosen, and the Stanford Research Institute (SRI) gave a demonstration of an open intestinal anastomosis to the Association of Military Surgeons of the United States. Following this demonstration, the military assigned Richard Satava to be program manager for Advanced Biomedical Technologies of the government-run Defense Advanced Research Projects Agency (DARPA). As a result, the Green Telepresence Surgery System was developed with the goal of improving surgical capabilities on the battlefield. The model was based on putting the robotic arms in an armored vehicle entitled the Medical Forward Area Surgical Team (MEDFAST) that could be driven directly to the battlefront. The surgeon console would be inside a Mobile Advanced Surgical Hospital (MASH) where the surgeon could operate at a safe distance, about 10–35 km, from the MEDFAST. A pivotal point for the Green Telepresence Surgery System came 1994 when Jon Bowersox, the medical scientist for the program, performed an intestinal anastomosis on ex-vivo porcine intestine using a wireless microwave connection between a MASH test and a MEDFAST vehicle. This landmark event was the first remote telesurgical procedure and prompted Frederick H. Moll, a surgeon and an entrepreneur, to acquire the license to the telepresence surgical system and create Intuitive Surgical Inc.

The SRI system was refined by Intuitive Surgical into a prototype known as "Lenny" (short for Leonardo) which was tested in 1997. In March 1997, the first clinical robotic

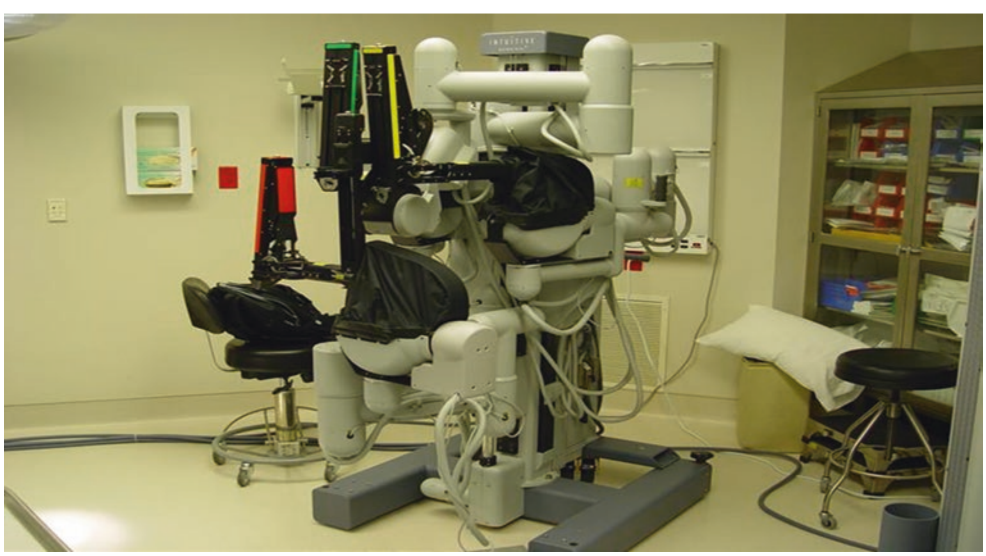

Fig. 3.1 Arms of the standard daVinci robotic surgical system

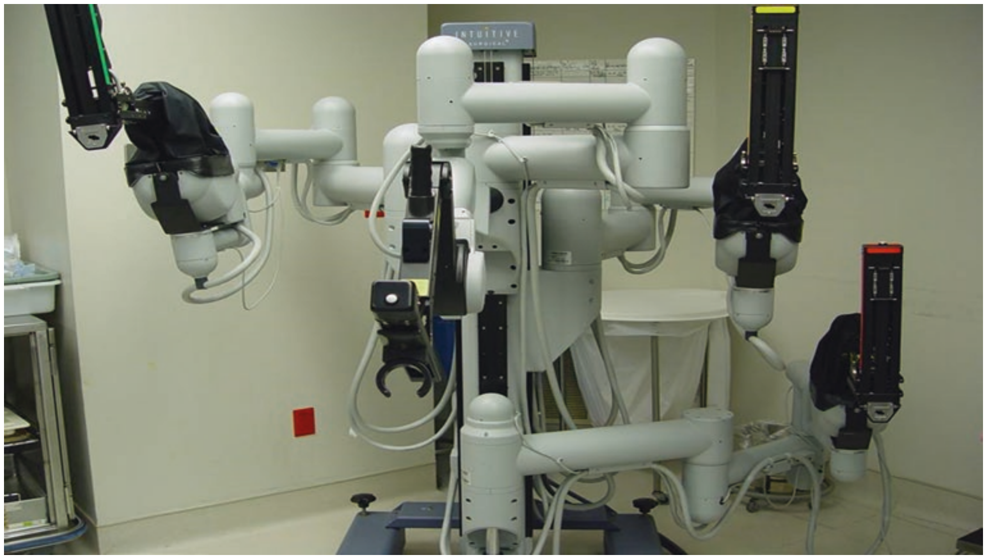

Fig. 3.2 Close-up view of the arms of the standard daVinci robotic surgical system

Fig. 3.3 Surgical console of the standard daVinci robotic surgical system

Fig. 3.4 daVinci S robotic surgical system during a robotic thoracic surgical procedure circa 2011

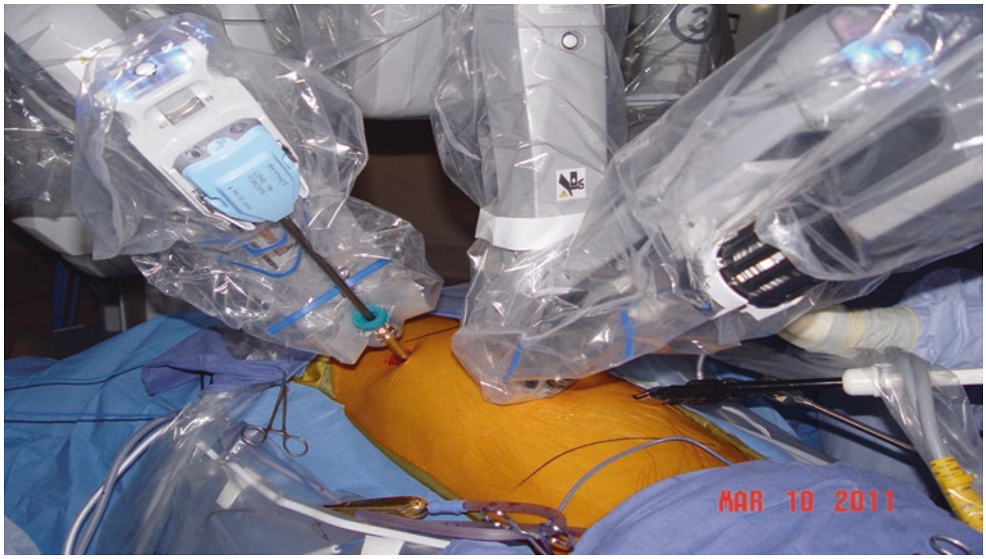

Fig. 3.5 Close-up view of the daVinci S robotic surgical system during a robotic thoracic surgical procedure circa 2011

Fig. 3.6 da Vinci Si system

Fig. 3.7 da Vinci Si during a robotic laparoscopic procedure circa 2015

Fig. 3.8 Consoles of the da Vinci Xi system

procedure, a cholecystectomy, was performed by Cadiere and Himpens in Brussels, Belgium, using a da Vinci robot. The first robot-assisted cardiac procedure was performed with the da Vinci system in May 1998 and the first closed chest coronary artery bypass graft was performed in June 1998. The da Vinci system was approved for general laparoscopic surgery applications in July 2000. In 2001, the da Vinci surgical system was approved for prostate surgery. In 2003, intuitive surgical merged with computer motion which ultimately resulted in the phase out of the Zeus system.

As of 2018, there were more than 4986 robotic surgical systems in hospitals worldwide, and more than six million robotic surgical procedures had been performed worldwide.

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