FRONTIERS

Focused Ultrasound: Relevant History and Prospects for the Addition of Mechanical Energy to the Neurosurgical Armamentarium

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Although the concept of focused ultrasonography emerged more than 70 years ago, the need for a craniectomy obviated its development as a noninvasive technology. Since then advances in phased array transducers and magnetic resonance imaging technology have resurrected the ultrasound as a noninvasive therapeutic for a plethora of neurological conditions ranging from embolic stroke and intracranial hemorrhage to movement disorders and brain neoplasia. In the same way that stereotactic radiosurgery has fundamentally changed the scope and treatment paradigms of tumor and specifically skull base surgery, focused ultrasound has a similar potential to revolutionize the field of neurological surgery. In addition, focused ultrasound comes without the general complexity or the risks of ionizing radiation that accompany radiosurgery. As the quest for minimally invasive and noninvasive therapeutics continues to define the new neurosurgery, the focused ultrasound evolves to join the neurosurgical armamentarium.

INTRODUCTION

Ultrasonography had its advent with the development of sound navigation and ranging (SONAR) technology during World War I and debuted in medicine in the 1930s with the work of Karl Theodore Dussik in the detection of brain tumors. By the 1940s, researchers were using high frequency-focused ultrasound to create lesions in the brain; however, the need for a craniectomy obviated its development as a noninvasive technology. Advances in transducers and magnetic resonance imaging (MRI) technology resurrected focused ultrasound as a potential noninvasive therapeutic for a plethora of neurological conditions ranging from embolic stroke and intracranial hemorrhage to movement disorders and brain neoplasia. The development of phased arrays to correct for cranial distortion has eliminated the necessity for a cranial window, and the development of intraoperative MRI and MR thermometry has enabled improved targeting and control.

In addition to its noninvasive mechanism, focused ultrasound does not have the risks and implementation complications of ionizing radiation that are attributed to radiosurgery. Repetitive treatments are not associated with increased tissue damage. As the quest for minimally invasive and noninvasive therapeutics continues, focused ultrasound is evolving in practicality to join the neurosurgical armamentarium. In this article, we describe the development of ultrasound and focused ultrasonography with a look at the current status of focused ultrasound therapy in movement disorders, stroke, pain, epilepsy, and brain tumor therapy.

A HISTORIC PRIMER ON ULTRASONOGRAPHY (TABLE 1)

Early Development

The development of ultrasonography dates back to the 20th century BC when Vitruvius, the Roman architect and engineer wrote a treatise on the acoustics of theaters including a discussion on interference, echoes, and reverberation. The Greek philosopher, Pythagoras, continued this study in the 6th century BC; he wanted

Key words
- Essential tremor
- High frequency ultrasound
- Pain
- Sonoembolism
- Stroke
- Targeted tumor therapy
- Tumor ablation
- Ultrasound

Abbreviations and Acronyms
BBB: Blood brain barrier
CT: Computed tomography
HIFU: High intensity focused ultrasound
ICH: Intracerebral hemorrhage
MRI: Magnetic resonance imaging
SONAR: Sound navigation and ranging
tPA: Tissue plasminogen activator

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Table 1. Key Events and Personnel in the Development of High Intensity Focused Ultrasound

Time	Personnel	Event
20th century BC	Vitruvius	Treatise on the acoustics of theaters: interference, echoes, reverberation
6th century BC	Pythagoras	Study of harmony
1794	Lazzaro Spallanzani	Demonstrated that bats use echo reflections to navigate in dark
1826	Jean-Daniel Colladon	Used underwater churchbell to calculate speed of sound through water
1845	Christian Doppler Buys Ballot	Described the Doppler effect
1876	Francis Galton	Invented the silent whistle, sound in the ultrasonic range
1877	Lord Rayleigh	Published "The Theory of Sound": sound as a mathematical equation
1880	Pierre and Jacque Curie	Demonstrated the Piezoelectric effect
1915	Paul Langevin	Invented the hydrophone to detect icebergs and submarines
1927	Robert Williams Wood Alfred Lee Loomis	Described the influence of sonic waves through liquids
1930s	Karl Theodore Dussik	Used ultrasonography to study the human brain
1944	John G. Lynn Tracy J. Putnam	Published results of high intensity focused ultrasound on the central nervous system
1950s	John Julian Wild	Diagnosed gastric cancer using ultrasound
1954	Petter Aron Lindstrom	Reported successful effects of high intensity focused ultrasound lesioning in pain
1958	Ian Donald	Diagnosed cystic ovarian mass using ultrasound
1960	William Fry Russel Myers	Used high intensity focused ultrasound to treat patients with Parkinson disease
1970s	Interscience Research Institute	First automated, computer-controlled image-guided high intensity focused ultrasound system for brain tumors developed
1980s	F. L. Lizzi	First Food & Drug Administration-approved focused ultrasound system: Sonocare CSF-100 for glaucoma

to understand why certain musical intervals seemed more harmonious than others. This study of acoustics, the transmission, propagation, and refraction of sound waves continued into the 18th century when in 1794, Lazzaro Spallanzani, an Italian biologist, demonstrated that bats use echo reflections from high frequency ultrasound to navigate accurately in the dark. In 1826, Swiss physicist, Jean-Daniel Colladon, in an experiment considered the birth of modern underwater acoustics, used an underwater churchbell (the first transducer) to calculate the speed of sound through water (**Figure 1**). This was followed in 1876 when Francis Galton invented the dog whistle, also known as the silent whistle, which emitted sound in the ultrasonic range only audible to certain animals. Concurrently, Lord Rayleigh, in 1877 published the "The Theory of Sound," which was the first description of the sound wave as a mathematical equation, thereby forming the basis of future work in acoustics and ultrasonography (19, 38).

In 1845, Austrian physicists Christian Doppler and Buys Ballot described the Doppler Effect, which postulated that the observed frequency of a wave depends on the relativity of the source and the observer. This observation, in addition to the work of Pierre and Jacque Curie (the Piezoelectric effect (**Figure 2**) in which they

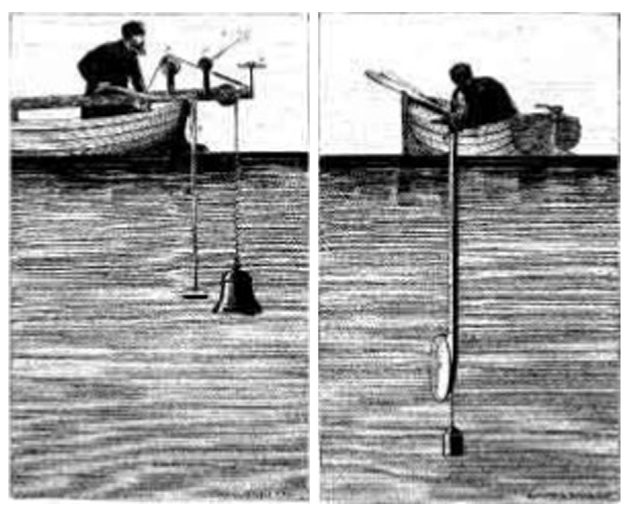

Figure 1. Jean Daniel Colladon uses an underwater church bell as a transducer to calculate the speed of sound through water.