Charles Lindbergh's contribution to high-altitude aviation, 1942-1944

Charles A. Lindbergh, 25-years-old, May 30, 1927, nine days after completing the first-ever solo transatlantic flight. Public domain

Jonathan D. Reich, MD, M Sc Eng; Michael G. Cooper, MB; and Isaac J. Reich

Dr. Reich is an Adjunct Associate Professor, George Washington University School of Medicine, Department of Pediatrics, Division of Pediatric Cardiology, Children's National Medical Center, Washington, DC.

Dr. Cooper is a Senior Anesthesiologist, St. George Hospital, Kogarah; and The Children's Hospital at Westmead, Sydney, Australia.

Mr. Isaac Reich is a graduate student at the University of South Florida, Tampa, FL.

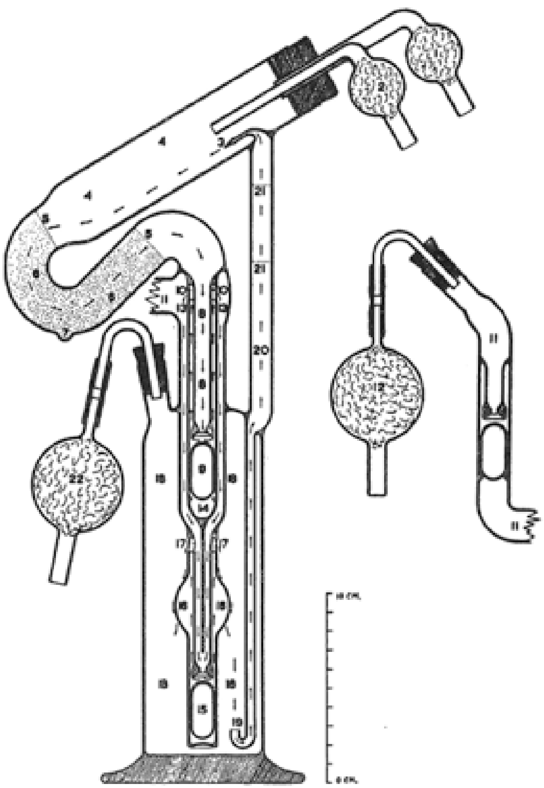
On May 21, 1927, Charles A. Lindbergh landed safely in Paris, completing the first solo transatlantic flight. In December 1930, he began a career in science that resulted in the development of the first in vitro cardiac perfusion pump, which was displayed at the Congress of Experimental Cytology in 1937.[1]

Lindbergh lived in Europe from 1935-1939,[2] when he was invited by Germany to visit its Air Force facilities. These visits were controversial in the United States but exposed Lindbergh to the advanced state of German aviation technology.[2] In 1940, Lindbergh was dismayed by America's support for Britain in its fight against Germany and he became a leading spokesman for isolationism. This led to Lindbergh resigning his commission in the U.S. Army Air Corps and a major conflict with President Roosevelt who was convinced Lindbergh was a Nazi.[2,4] Thus, when the U.S. entered World War II, Lindbergh was a controversial figure disliked by many Americans and Roosevelt refused to let him renew his commission.[2]

Lindbergh wrote in his journal, "I simply cannot remain idle while my country is at war. I must take some part in it."[5] Roosevelt's Interior Secretary Harold Ickes wrote a memo to Roosevelt stating, "…he [Lindbergh] is a ruthless and conscious fascist, motivated by a hatred for you personally and democracy in general…I ardently hope that this convinced fascist will not be given the opportunity to wear the uniform of the United States. He should be buried in merciful oblivion." Roosevelt responded, "I agree wholeheartedly."[2]

Unable to rejoin the U.S. armed forces, Lindbergh took a job as a test pilot for the Ford Motor Corporation, at the country's largest factory producing combat aircraft, located outside Detroit, Michigan. It was through this position that he was introduced to Dr. Walter Boothby, the head of Aviation Medicine at the Mayo Clinic in 1942.[2-6]

Boothby was a pioneer in the field of high-altitude physiology. He had been a co-inventor of the standard



The Lindbergh-Carrell cardiac perfusion pump as displayed at International Congress of Cytology in 1937. This pump would demonstrate for the first time an organ could be maintained on an extracorporeal circuit. The circuit used a perfusion fluid rich in oxygen filtered by two platinum screens designed to prevent infection. All components were autoclaved in an attempt to achieve sterility. Both the blood that entered the organ and the blood removed from the organ were passed through a silica and sand filter, and cotton was used to plug holes to try to prevent infection. A glass rotating pump, powered by compressed air pumped the blood through the organ.[1] Public domain

Charles Lindbergh, 40-years-old, undergoing an experiment in the high altitude simulator at the Mayo Clinic, 1942. *Photo 1 at History - Department of Defense Medical Research Office - Mayo Clinic Research*

aviation mask: the BLB Oxygen Mask.[6] Boothby was the director of the Aero-Medical Institute at the Mayo Clinic, with a recently developed state-of-the-art high-altitude simulator.[2,5,7] Lindbergh would act as a subject for experiments in the simulator designed to replicate flying conditions at altitudes exceeding 40,000 feet, and was a test pilot to evaluate the effectiveness of masks and other equipment designed to support pilots at high altitudes.[2]

The evolution of high-altitude aviation prior to World War II

During the 1930s, several advances were made in aircraft design that allowed increases in altitude; the ratio of compressed air to fuel was reduced by cooling air, thereby allowing for greater power, the development of high lift wings was advanced, and the invention of pressurized suits for pilots was perfected. As a result of these advances, the record for achieving high altitudes was gradually extended until by 1937 an altitude of nearly 54,000 feet (16,300 meters) was reached.[8]

However, not every problem of flight above 40,000 feet elevation was solved. Above 40,000 feet a pilot loses consciousness in about 10 seconds without supplemental oxygen. Oxygen tanks were heavy, combustible, and the removal of carbon dioxide from the breathing circuit subjected the pilots to possible soda lime dust contamination, which resulted in irreversible lung damage (as portrayed in the movie *Midway*).[9]

Solutions to some of the engineering challenges involved in peacetime flying altitudes had been achieved in the 1930s; however others, such as the need for all apparatus to function properly at extremely cold temperatures, continued to persist.[10] Combat presented an entirely new set of challenges.

Boothby had been a chief surgeon in World War I and operated on wounded soldiers in several major battles. He became interested in the plight of pilots and their need for supplemental oxygen. It became recognized that hypoxia contributed to pilot error, and the masks of the era were ill fitting and tended to fill with ice.[7] This was the inspiration for the development of the BLB aviation mask for which Boothby, William Randolph Lovelace II, and Arthur Bulbulian applied for a patent in 1938.[7]

Overcoming the technologic challenges of engaging in combat above 40,000 feet in elevation was a strategic objective for the major combatants in World War II. The Germans, Americans, and Russians all strove to solve the engineering and medical challenges of accomplishing it, and thereby achieve a significant military advantage. The Germans had invested significantly more resources than the allies in this endeavor prior to World War II. During his visits to Nazi Germany, Lindbergh was exposed to advances Germans had made in aviation,[2] including high-altitude simulation chambers, pilot training programs, and specialized oxygen supply valves to provide more oxygen at higher altitudes.[10]

Physiologic considerations at high altitude

The physiologic issues of high-altitude aviation are complicated and not completely solved by providing supplemental oxygen. When breathing pure oxygen at 40,000 feet a pilot's arterial oxygen saturation drops from 99 percent to 84 percent and at 50,000 feet it drops to 15 percent.[11] The metabolism of nitrogen is a complicated problem referred to as decompression sickness.

As a human ascends to higher altitudes the partial pressure of oxygen (pO_2) in the atmosphere decreases, but the partial pressure of carbon dioxide (pCO_2) remains relatively constant. As a result, the ratio of pO_2 to pCO_2 decreases. Chemoreceptors sense elevated carbon dioxide (hypercarbia) rather than low oxygen (hypoxia). The compensatory mechanism induced, hyperventilation, reduces the amount of carbon dioxide in the blood. The ensuing reduction in the $PaCO_2$ causes respiratory alkalosis.[11]

The body compensates for respiratory alkalosis by inducing a metabolic acidosis through renal secretion of bicarbonate. Eventually the kidneys can bring the pH of the blood close to the normal upper level of 7.45. However, this takes two to three days. In the meantime, the effects of alkalosis are sleep disturbances, impaired mental performance, weight loss, and decreased exercise capacity.[11]

This constellation of symptoms is referred to as acute mountain sickness, and, today, it can be prevented by using the diuretic acetazolamide prior to ascending to high altitudes. Acetazolamide replicates the body's

The BLB mask developed by Dr. Walter Boothby and patented in 1938. It was effective in maintaining pilot oxygenation at less than 40,000 feet elevation. *Permission granted by Dr. Michael Cooper*

The inside of the A-14 aviation mask developed at the Mayo Clinic with Lindbergh's contribution. The white box demonstrates the relationship of the vents to the right and left of the pilot's mouth that were designed to remove water vapor. Carbon dioxide had to be removed by soda lime which can potentially cause lung damage. *Courtesy of 303rd Bombing Group* compensation for respiratory alkalosis by preventing the kidney from reabsorbing bicarbonate. Acetazolamide has side effects;most notably it lowers serum potassium which in turn can cause arrhythmias if adequate potassium supplementation is not provided.[11]

There are two other significant complications of acute mountain sickness: high altitude pulmonary edema, and high altitude cerebral edema. The pathophysiology of these complications involves multiple factors, both of which can be lethal.[11]

The physiology of nitrogen

Air is 79 percent nitrogen. At sea level, absent an acute change in pressure, nitrogen passes inconsequentially through the various tissues and out of the body. Nitrogen has no physiologic effect and acts as an inert bystander. More than half of the body's nitrogen resides in fat cells, because nitrogen is more soluble in fat than in liquid.[11]

Disparate nitrogen dissolution in different tissues results in diverse effects depending on the length of time a person is exposed to external pressure. Scuba divers can descend to deep depths for short periods of time without experiencing adverse effects of rapid ascent to the surface. This is because it takes time for nitrogen to dissolve in fat cells, and in short periods little of it dissolves.[11]

Decompression sickness is known as the "bends." In historical literature, it is sometimes referred to as the (staggers). If a person experiences a decrease in external pressure at a rate that allows the tissues to become supersaturated with nitrogen, bubbles form in the blood. This happens if one returns to sea level after being exposed to high pressure while diving. It can also occur during quick ascents with prolonged exposure to high altitude in an unpressurized aircraft or rapid decompression in a pressurized aircraft.[12] These bubbles lodge in various tissues. If they lodge in the bones they cause bone pain, i.e., the patient is bent over in pain thus the "bends," or if it lodges in the brain it affects cognition, i.e., the patient stumbles around thus the "staggers."[11]

Charles Lindbergh, spokesperson for the America First Committee (AFC), speaks during a rally October 30, 1941 at Madison Square Garden in New York City. The AFC was the pressure group against the Americans joining World War II. Irving Haberman/IH Images/Getty Images

The physiology of nitrogen metabolism associated with abrupt decreases in external pressure was well known in 1942. Doctors had studied and reported on workers on the Golden Gate Bridge in 1933 who descended to high external pressures to work on the foundation deep in San Francisco Bay. If they returned to the surface quickly they often got sick. Doctors attending to these workers had established one of the first working decompression chambers.

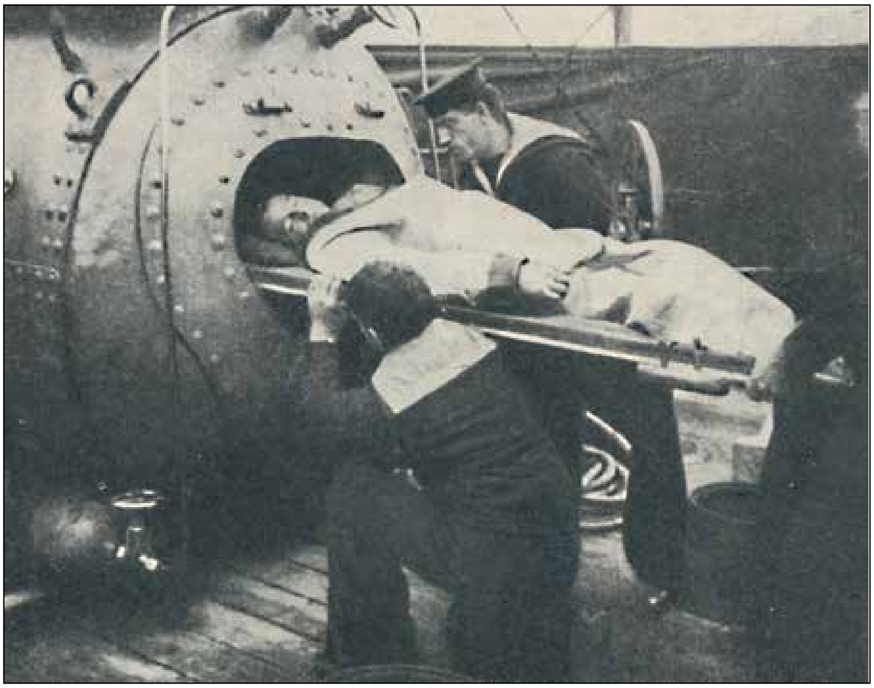
Exposure to high altitudes in combat

Flying at high altitudes in combat presented several unique challenges. The time needed to remain at high altitudes was longer and required better, lighter, and more efficient oxygen supplies including better pilot masks. However, the time to ascend and descend from high altitudes would need to be shorter. In addition, pilot ejection needed to be done safely. Pilots in combat have a greater need to eject and ejection above 40,000 feet requires a portable jump-mask with a portable oxygen supply. Pilots also needed specific and extensive training on the unique challenges of engaging in combat above 40,000 feet, including how to deal with problems relating to nitrogen physiology.

Germany had been addressing these challenges for at least five years before the Allies. In addition to specialized training simulators, the Germans were at the forefront of developing better oxygen equipment, pressurized cabins, heated gloves, and improved heated pilot suits.[10] The Germans were studying whether a pilot could withstand sudden loss of pressure if the cabin were pierced by enemy ordinance. To study this, they frequently used prisoners without their consent. On occasion, they would kill the prisoners following the tests to do pathophysiologic studies of their cadavers.[10]

These experiments were dangerous. At least three times Lindbergh passed out in the simulation chamber and even when he did not pass out, exposure to hypoxia is unpleasant and produces symptoms Lindbergh compared to a hangover.[5] In the spring of 1943, due to instrumentation failure, Lindbergh lost consciousness while piloting a plane solo at 36,000 feet. Realizing he was losing consciousness he put the plane into a dive. The plane descended approximately 20,000 feet unpiloted before he regained consciousness.[2] The previous year the cockpit filled with smoke during another test flight.[5]

The risks Lindbergh accepted to do this research were admirable considering he was too old to be required to serve. The upper age limit for the draft was 35-years-old, and Lindbergh was 42-years-old when he flew in combat.[13]



A recompression chamber, 1936. Photo by The Print Collector/Getty Images

Advances made by Lindbergh and Boothby

The historical record documents the following advances:[14-16]

- Testing and combat-simulation use of masks and improved oxygen equipment for American pilots,[17] including the development and introduction of the A-14 pilot mask specifically designed for prolonged flights at high altitudes.
- Improvements in technology for pilot ejection at high altitudes, including the development of jump-masks that included a portable oxygen supply.
- Improvements in the simulation of pilot ejection descent and the establishment of the optimal flow rate for oxygen during ejection descent.
- Experimentation that demonstrated denitrogenization could be performed safely and would prevent complications of rapid changes in air pressure.
- The development of an official pilot training protocol to prepare pilots for high-altitude combat.

Supplemental oxygen experiments

Initial simulations of high-altitude aviation and simulated ejection demonstrated that standard U.S. military pilot oxygen equipment was inadequate. In the initial experiments simulating parachute descent, Lindbergh demonstrated ill effects of hypoxia, including altered consciousness and impaired decision-making, forcing him to reconnect to the simulator's non-portable oxygen supply.[5,14]

Lindbergh performed tests on negative pressure demand oxygen masks with a constant flow feature in simulated and actual flights at and above 40,000 feet. He demonstrated that 43,000 feet was the altitude limit for the standard BLB mask, and contributed to the development of specialized pressure masks allowing for flight at higher altitudes,[5,15,16] and the introduction of the A-14 aviation mask in 1943. Using this mask, Lindbergh reached a peak altitude of 48,000 feet in the simulator without demonstrating ill effects, thus demonstrating that given the right equipment a pilot could engage in combat at this altitude.[5,16] The Mayo Clinic Section of Aeronautical Medicine and Lindbergh were given significant credit in the development of this mask.[17] Because it resulted in less oxygen loss, Lindbergh credited this mask for saving his life in the incident where he lost consciousness at 36,000 feet in 1943.[17]

Pilot ejection simulations consisted of Lindbergh sitting in the simulator and when air pressure and oxygen levels simulated altitudes exceeding 40,000 feet, he would replace the cockpit mask with a jump-mask and then perform exercises equivalent to a pilot preparing to eject (some experiments involved simulating the hatch jamming or oxygen equipment malfunction). Once simulating being out of the plane, the simulator would approximate atmospheric changes consistent with a parachute jump, i.e., the oxygen level and air pressure would gradually increase per minute simulating a pilot returning to sea level. Over time the protocol was adjusted to more accurately represent atmospheric changes during a pilot's descent.[5,16] These experiments resulted in the development of jump-masks that consisted of a mouthpiece attached to a parachute oxygen bottle. Lindbergh proposed an optimal oxygen flow rate and made equipment recommendations, particularly for the jump-mask mouthpiece.[5,16]

The Ford Company's factory at Willow Run where Lindbergh worked for about two years, produced nearly half of the B-24 bombers used during the war.[18] Many of Lindbergh's recommendations for improved oxygen equipment were adopted by Ford in the production of combat aircraft.[2,13,19]

Denitrogenization

Lindbergh worked on protocols to rid the pilot's body of nitrogen before ascending to high altitude. He would undergo various protocols of denitrogenization, then perform rapid ascents to altitudes above 40,000 feet and remain at these altitudes for at least an hour because the longer a pilot is exposed to high altitude the greater his risk of decompression sickness.[12,15,16] Demonstrating no ill effects of the bends, Lindbergh demonstrated denitrogenization was an effective means of preventing adverse medical effects of nitrogen metabolism in combat pilots.[5] The records do not provide the altitudes and times of every flight, but in the simulator Lindbergh ascended to 35,000 feet in less than three minutes and 40,000 feet in seven minutes after denitrogenization.[15] In flight, he reached 43,000 feet with rapid ascents and descents, after which he did not report any symptoms as described during flights on February 11, 1944.[5]

The initial protocol consisted of exercising for half an hour while breathing inhaled air which contained no nitrogen. Once this was proven an effective means of ridding the pilot's body of nitrogen, Lindbergh worked on perfecting a technique more appropriate for the time constraints necessitated by the realities of combat. He worked on reducing the length of time of exercising and various breathing techniques that could shorten the time a pilot needed to rid his body of nitrogen in preparation for combat at elevations exceeding 40,000 feet.[5]

Pilot training protocol

In July 1936, as part of his much-criticized visits to Germany, Lindbergh visited the Richthofen Geschwader pilot training program.[2] High-altitude training was part of German pilot training, but to what extent Lindbergh adopted German techniques in his pilot training recommendations for American pilots is not known.[10] It is possible that part, or all, of the American training program for high-altitude combat was borrowed from the Germans.

At the Mayo Clinic, Lindbergh authored a confidential memo in October 1942 that was later adapted to an undated five-page manual detailing the first known American training program for high-altitude aviation.[16,22] Lindbergh believed not only would pilot training improve safety at high altitudes, but pilots could be trained to recognize symptoms of hypoxia and take appropriate actions.[20] This document, circa 1943, details three months of lectures and training procedures to ensure safe aviation and ejection at high altitudes.[20] Lindbergh's pioneering recommendation that pilots be trained in high-altitude aviation and ejection techniques at high altitude pressure conditions was widely adopted.[20]

Lindbergh in the South Pacific

On April 24, 1944, Lindbergh got his wish and left the U.S. for combat in the South Pacific. There, he fulfilled his dream of fighting in combat for his country.[2] He flew combat missions against the Japanese in New Guinea and Palau.[2,5] This would end any further experimentation by Lindbergh in the new field of high-altitude aviation. His commanding officer, Colonel Charles MacDonald, said of him:

> Lindbergh was indefatigable. He flew more missions than was normally expected of a regular combat pilot. He dive-bombed enemy positions, sank barges, and patrolled our landing forces on Noemfoor Island. He was shot at by almost every anti-aircraft gun the [Japanese] had in Western New Guinea.[2]

After flying 50 combat missions Lindbergh was sent home in September 1944.[2] The highest altitude Lindbergh reached in combat was 30,000 feet.[5]

High-altitude aviation

High-altitude combat did not occur with any frequency during World War II, but was often experienced in the Korean and Vietnam conflicts. Starting in the late 1950s, U.S. spy planes cruised at 70,000 feet elevation for hours.[21]

Research done at the Mayo Clinic and elsewhere, gave the U.S. a strategic advantage that allowed for high altitude flights over the Soviet Union. These flights provided military intelligence and detailed information about everyday Soviet life.[21] Although the Soviet Union was aware of these flights, their inferior technology didn't allow them to interfere for several years.[21]

In 1960, the Soviets shot down a flight at 68,000 feet in the famous U2 spy incident. U.S. pilot Francis Powers safely parachuted to the ground from an altitude no pilot had ever successfully ejected.[21] In 1962, U2 flights exceeding 70,000 feet in elevation photographed evidence the Russians were placing nuclear missiles in Cuba, thus starting the Cuban Missile Crisis.[21] With this photographic evidence, the U.S. Ambassador to the United Nations, Adlai Stevenson, was able to prove Soviet dishonesty.

U2 pilots underwent intensive training, the origins of which can be found in Lindbergh's proposals.[21] This flight training, including techniques for safe pilot ejection, were essential to U.S. national security.[21]

Lindbergh's contributions to high altitude aviation are recognized for their importance and for the bravery and the patriotism required to conduct these experiments. Because standard issue oxygen equipment used by the U.S. military prior to 1942 was so ineffective and frequently resulted in pilots losing consciousness, improvements in equipment and training made by Lindbergh and Boothby have saved the lives of numerous American pilots.[2]

References:

1. Sade RM. A Surprising Alliance: Two Giants of the 20th Century, Ann Thoracic Surgery. 2017; 103: 2015-9.
2. Berg AS. Lindbergh. New York: Berkley Publishing. 1998; 355-455.
3. Cole WS. Charles A. Lindbergh and the Battle Against American Intervention in World War II. New York: Harcourt, Brace and Jovanovich. 1974; 3-14.
4. Wallace M. The American Axis. New York: St. Martins's Press. 2003; 306-8.
5. Lindbergh CA. The Wartime Journals of Charles A. Lindbergh. New York: Harcourt, Brace and Jovanovich. 1970; 175-929.
6. Card WI, Forest Smith J, Griffeths WJ, McSweeny BA, et al. The BLB Mask for administering Oxygen. The Lancet. 1940; 235: 398-402.
7. Cooper MG, Street NE. High Altitude Hypoxia, a Mask and a Street. Anesth Intensive Care. History Supplement. 2017; 45-8.
8. Hawkins MF. Some Problems of High Altitude in the 1930s: A World Record Attempt. Aviation Space and Environmental Medicine. 1995; 66: 1212-4.
9. Lauria JI. Soda Lime Dust Contamination of Breathing Circuits, Anesthesiology.1975; 42(5): 628-9.
10. Kehrt, C, 'Higher, Always Higher' Technology, the Military, and the Science of Aviation Medicine During the Age of the Two World Wars, Endeavor. 2006; 30: 138-43.
11. Guyton AC, Hall JE. Textbook of Medical Physiology, 11th Ed. Philadelphia: Elsevier and Saunders. 2006; 514-51.
12. Federal Aviation Administration. Altitude-Induced Decompression Sickness. Pilot Safety Brochure. FAA.gov. https://www.faa.gov/pilots/safety/pilotsafetybrochures/media/DCS.pdf.
13. Olsen L. Those Angry Days: Roosevelt, Lindbergh, and America's Fight Over World War II, 1939-1941. New York: Random House. 2013; 197-223, 441.
14. Lindbergh, CA. Experimental notes, September 26, 1942. (Provided by request by the Mayo Clinic.)
15. Lindbergh, CA. Experimental notes, September 27-28, 1942. (Provided by request by the Mayo Clinic.)
16. Lindbergh, CA. Notes describing various jump mask experiments, October 3, 1942. (Provided by request by the Mayo Clinic.)
17. Lindbergh CA. Of Flight and Life. New York: Scribner and Sons. 1947; 5-82.
18. Willow Run. Encyclopedia of Detroit. Detroit Historical Society. Detroithistorical.org. Available at:https://detroithistorical.org/learn/encyclopedia-of-detroit/willow-run.
19. Charles Lindbergh: Scientist. Charles Lindbergh House and Museum. Minnesota Historical Society. https://www.mnhs.org/lindbergh/learn/other-occupations/scientist.
20. Lindbergh, CA, Outline for 3-month indoctrination program, circa 1943.
21. Reel M. A Brotherhood of Spies. New York: Doubleday Publishers. 2018; 175-296.

Acknowledgment

The authors would like to acknowledge the help of Dr. Shiva Sharma of Emory University School of Medicine, retired, for his help reviewing the manuscript.

Corresponding author's E-mail is reich.isaac1@gmail.com.