# DAVID BODIAN

*1910-1992*

*A Biographical Memoir by*

*MARK E. MOLLIVER*



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NATIONAL ACADEMY OF SCIENCES

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*May 15, 1910–September 18, 1992*

BY MARK E. MOLLIVER



DAVID BODIAN WILL BE REMEMBERED as one of the most innovative neuroscientists of the 20th century. Committed to science, humanity, and education, he never sought recognition or power. His demeanor was marked by gentle modesty and dedication to colleagues and students. David's kindness and modesty are inspiring in view of his numerous contributions to biomedical science, especially his role in one of the most significant biomedical advances of the past century. Over the course of his career he made discoveries that provided the groundwork for development of the polio vaccine that has nearly eradicated poliomyelitis, one of the most feared diseases in the world. Production of the vaccine was an urgent national priority that depended on the contributions and collaboration

of many researchers, and was marked by intense competition and drama. I will summarize a few highlights of Bodian's role in the polio adventure, and refer you to a fascinating account of the polio story in the book *Polio: An American Story* (Oshinsky, 2008).

David Bodian was born in St. Louis, Missouri, on May 15, 1910, and died in Baltimore at age 82 on September 18, 1992. He grew up in Chicago, where his parents moved in 1913 when he was three years old. He was the oldest son and the third of six children, with four sisters who were talented in writing and literature. His parents immigrated to the United States in 1908 from their original family home in the Ukraine—the small town of Caro-Constantinov, located near Kiev. In Chicago his father owned a dry cleaning shop until forced into bankruptcy during the Great Depression of 1929. Due to the Depression the Bodian family lived at the edge of poverty and was supported by the two oldest daughters. Despite their financial difficulties, his family strongly embraced a tradition of learning. Since there was little money for normal childhood activities, David made his own toys and spent many days reading novels in his special haven, the Chicago public library. He attended a Chicago public high school, which provided a sound primary education, and he later spoke of being inspired by a new high school science course that included laboratories for problem solving and inquiring into the workings of nature.

Based on his intelligence and excellent academic performance, Bodian finished high school in three years and entered Crane Junior College. He soon transferred with advanced standing to the University of Chicago, where he became fascinated by biology and received a B.S. degree in zoology in 1931. Following college he planned to get a job to support his family but was encouraged by his teachers and family to enter the Ph.D. program in zoology at the University of Chicago after he received a scholarship. He was able to supplement his limited finances by working as a teaching assistant in neuroanatomy throughout his years of graduate and medical school. His graduate research on the opossum visual system was successful and he received a Ph.D. degree in anatomy in 1934. Despite initially thinking that he was unlikely to proceed in higher education, he received a graduate scholarship of $300.00 that amounted to one year's tuition and enabled him to enroll in the medical school at the University of Chicago, where he earned the M.D. degree in 1937.

In talking with David (when I was a postdoc) he attributed his good fortune largely to the influence of the supportive faculty members at the University of Chicago. David exemplifies the young student inspired by a series of outstanding neuroscientists on the Chicago

During and after the Great Depression, charitable contributions for science were scarce, and large gifts for research virtually disappeared. After working one year with Howe, his fellowship was terminated due to the severe economic crisis.

faculty and he later expressed gratitude that they treated graduate students as friends and equals. His thesis adviser, C. Judson Herrick along with Norman Hoer and G. W. Bartelmez, were among the leading neuroanatomists in Chicago. Long before neuroscience became a recognized academic field, the University of Chicago assembled a sizeable group of faculty members with expertise in brain research. Dr. Bodian had the opportunity to study with J. Z. Young, Ralph Gerard, and Paul Weiss. Among his other influential teachers were Karl Lashley, Steven Polyak (of retina fame), and Percival Bailey. In medical school one of his mentors was A. Earl Walker (later chair of neurosurgery at Johns Hopkins) and he also studied with Paul Bucy and Heinrich Kluver (who discovered the Kluver-Bucy Syndrome). Largely due to his intellect and curiosity about science, he was deeply influenced by the teachers in his environment. He later recalled being inspired by the embryologist Benjamin H. Willier and taking four graduate courses with him. Their friendship was renewed later at Johns Hopkins, where Willier served as professor and chair of biology on the Homewood campus from 1940 until 1958.

Several fortuitous events influenced the course of Bodian's career following medical school. Initially, in 1938, he received an eight-month National Research Council postdoctoral fellowship at the University of Michigan to work with Dr. Elizabeth Crosby, who was interested in what could be learned about brain function from comparative neuroanatomy. Near the end of 1938 he was quite surprised to receive an invitation from Howard Howe to join him in the study of polio as a postdoctoral fellow at Johns Hopkins. Howe wrote, "Our attempt to study virus diseases from the standpoint of a neurophysiologist and anatomist…appears unique and carries with it all the excitement…of pioneering in a new field. I think you would find it fascinating." At that time, in 1939, financial support for research was severely limited. During and after the Great Depression, charitable contributions for science were scarce, and large gifts for research virtually disappeared. After working one year with Howe, his fellowship was terminated due to the severe economic crisis.

Bodian reluctantly returned in 1940 to the cold weather of the Midwest as an assistant professor of anatomy at Western Reserve in Cleveland, Ohio. After spending several months in Cleveland, Howard Howe notified Bodian that the National Foundation for Infantile Paralysis (the National Foundation) had offered a $300,000 grant for five years to set up a large polio laboratory in the Johns Hopkins School of Public Health (now the Johns Hopkins Bloomberg School of Public Health,) with funding to be renewed later if they made progress. Howe invited Bodian to return and join him on the faculty in the Department of Epidemiology to study poliovirus infection. Bodian found this prospect for research attractive, yet he was uncomfortable about

prematurely leaving his new position at Western Reserve. He expressed concern that he had no training in epidemiology. The decision was resolved when he received a call from Lewis Weed, chair of anatomy and dean of the medical school at Hopkins. Weed requested that Bodian come to Hopkins immediately to oversee development of the new Polio Lab and indicated that Howe had become ill, requiring abdominal surgery. This opportunity was a turning point in his career since Bodian was a neuroanatomist with little background in virology or infectious disease. Yet he happily returned to Johns Hopkins in 1942 as an assistant professor in anatomy and epidemiology and soon became energetically immersed in studying the pathogenesis of poliomyelitis.

The Great Depression was a disastrous era economically, yet it led to a new mechanism for support of biomedical research. Franklin D. Roosevelt had been elected President after recovering from a severe episode of poliomyelitis at age 39 that left him paralyzed from the waist down. Having spent years struggling to recover the use of his legs, he remained unable to stand without braces, yet he mounted a vigorous campaign for the Presidency of the United States, and was elected by a large majority. As a result of his traumatic, personal experience with paralytic polio, FDR was committed to promoting the development of a cure for polio, starting the March of Dimes to raise money. In 1938 Roosevelt announced the creation of a new private foundation to raise donations for research and treatment of polio: The National Foundation, with his law partner Basil O'Connor as director. O'Connor was a close friend of FDR and a successful Wall Street lawyer but an odd choice since he had no training in science. In 1939 O'Connor invited Dr. Thomas Rivers to head a scientific committee developing an agenda for polio research. (Rivers, reputed to be a leading expert on viral infections, had received an M.D. degree from Johns Hopkins School of Medicine and then became the director of Rockefeller Hospital in New York.)

Based on his own scientific approach, Rivers set goals for polio research. Using research in basic science in order to understand the mechanism of the disease, Rivers planned first to study the pathology of poliomyelitis, and then determine mechanisms of entry and spread of the virus; at the end of his list he hoped to see a vaccine produced. The National Foundation initially offered three large grants to Johns Hopkins, Yale, and the University of Michigan to build virus labs and form polio research groups; the Johns Hopkins group was invited to study the neuropathology and determine how polio affected the nervous system.

## BODIAN'S EARLY RESEARCH

Bodian's research had previously been centered on neuroanatomy, with his main interest in analyzing neuronal pathways in the brain in order to understand

the basic patterns of neuronal circuits and connections. His Ph.D. thesis studied visual pathways in the opossum forebrain, a topic selected because opossums appeared to have a more complex forebrain than rodents. I suspect that an important initial factor was the lack of funds to purchase animals. Opossums were considered at the time nuisance animals, and Bodian could catch them by roaming the city late at night (the animals were attracted to trash barrels for food). In order to visualize axons and synaptic terminals in the brain, he developed a new stain for axons using a silver-protein complex called protargol, and added a photographic developer to detect the silver. He had learned that protargol was then used for the treatment of bladder infections, and he observed in the neuropathology lab that axons were deeply stained in bladder specimens from patients treated with protargol. After adding several improvements to the staining procedure, he published this method while still in graduate school. His new method soon became widely used for axon staining and was referred to as the "Bodian silver stain." The stain was later shown to bind to intermediate neurofilament proteins within axons. He subsequently applied the silver stain in goldfish and discovered the large synaptic bulbs from vestibular axons that terminated on Mauthner cells. Soon after publishing these results in 1937 and 1938, he was invited to join Howard Howe as a research fellow at Johns Hopkins. He had demonstrated careful, innovative research and developed a new method to stain axons, a technique that Howe predicted would prove useful to visualize motor neuron axons in their study of polio.

The collaboration of Bodian and Howe at Hopkins rapidly led to many new findings and publications, as they worked well together and became close friends. They initially reported (1939) that poliovirus was present in stools of affected patients and the infection appeared restricted to humans, a fact that greatly limited experimental studies. They soon found that poliovirus could infect chimpanzees and certain Old World monkeys, based on a report in 1935 that two chimpanzees in a children's zoo in Cologne, Germany, had been infected with a paralytic disease. After Bodian returned to Hopkins as a faculty member, they built a virology laboratory, including housing facilities for 6 chimpanzees and 100 monkeys in the center of the Hopkins medical campus. They verified that chimpanzees were readily infected with poliovirus by the oral route and that rhesus and cynomolgus monkeys could be infected by injection of virus into the brain or muscle, results that provided them with animal models for further research. Due to the use of chimpanzees, their studies of pathogenesis and histology of poliomyelitis proceeded at a rapid pace. Bodian published a now-classic description of spinal cord histopathology that detailed the course of neuronal injury and chromatolysis in motor neurons (both in human and monkey).

They then turned to the questions of portals of entry and mode of virus distribution (1940 and 1941) since the route of entry and the mechanism of spread were unknown. Entry of the virus through the nose to the olfactory bulb had been widely suspected, but Bodian's research did not substantiate that route. A heated controversy then persisted in the biomedical community as to whether poliovirus entered the nervous system by transport through the axons of infected peripheral neurons versus the alternative that the virus may spread from the blood stream to the nervous system due to viremia. Bodian and Howe first demonstrated intraneuronal virus distribution by fast retrograde axonal transport from muscle to spinal cord along the axons of motor neurons. They later found that viral spread through the blood stream was also a frequent route of nervous system infection. The oral route of virus entry into the gastrointestinal tract was highly infectious in chimpanzees and they detected high levels of poliovirus in blood before the onset of paralytic symptoms, indicating that dissemination often occurred by a bloodborne viremia. They later demonstrated that both routes permit central nervous system infection and that the initial and more common route of distribution is by viremia. Which route predominates remains unresolved even now, since both mechanisms are likely to occur depending on the specific virus type and host conditions. It remains unclear as to how the bloodborne virus penetrates the blood brain barrier during viremia, but Bodian showed that a local inflammation or injury can facilitate access. They soon addressed a more important question: the precise route by which oral infection leads to viral replication followed by viremia.

Bodian employed extensive histopathologic and immunologic studies to clarify the mechanism of virus spread and found that poliomyelitis initially is a gastrointestinal infection that begins with oral ingestion of the virus, typically by hand-to-mouth spread of contaminated stools. They identified high concentrations of virus in two sites that showed cytopathologic changes; one was in lymphocytes of the pharyngeal tonsils. However, the site of greatest virus infection was located in the wall of the small intestine, specifically the ileum, located in Peyer's patches, which are large lymphoid follicles a few centimeters in length. About 30 of these patches are present in the human ileum as elongated thickenings of the intestinal epithelium packed with lymphocytes. Most cells within these patches are B-lymphocytes, along with other lymphocytes. Orally ingested virus reach the B-lymphocytes from the intestinal lumen and rapidly replicate within these cells, yielding high concentrations of poliovirus. Some viruses are shed off into the gut and are expelled in feces where they become available for transmission from person to person.

Bodian confirmed that distribution of infected feces is the primary mode by which the disease is spread through the human population. Most of the infected B-lymphocytes in Peyer's patches are activated by the poliovirus and pass to mesenteric lymph nodes where the immune response is amplified and antibodies are produced. The antibodies then spread through the lymphatic system and enter the blood stream through the thoracic duct. Although Bodian recognized that poliovirus was highly selective for a particular set of lymphocytes and neuron types, the mechanism of specificity was not established until 50 years later when a poliovirus-binding site (named CD155) was identified as the polio receptor. Expression of CD155 is responsible for cell specificity of polio infection and is the crucial factor that facilitates endocytosis of the virus into lymphocytes and motor neurons (Mendelsohn et al., 1989; Iwasaki et al., 2002). (CD155 is an immunoglobulin that normally functions to establish intercellular junctions between cells. Since CD155 is located in the plasma member of particular cells and has an extracellular binding site for poliovirus, it allows virus to readily enter these cells). The selective distribution of CD155 in lymphocytes and motor neurons determines the cell types that are most vulnerable.

Bodian and Howe demonstrated, in 1941, that poliovirus is present in the blood stream before onset of symptoms and is followed by a rapid antibody response within seven days of infection. They found that the appearance of polio antibodies rapidly terminated the viremia. This result suggested a narrow time window when the virus was able to enter the central nervous system (CNS), and strongly supported the hypothesis that antibodies produced by a vaccine could prevent the paralytic infection. However, their data also demonstrated the importance of timing, since viruses that are undergoing axon transport are enclosed within the axons and protected from the antibody so that they could later infect the CNS. It was therefore found crucial that immunization be done prior to infection to prevent the viremia from reaching muscle where it can the enter motor neuron axon terminals.

Polio research led Bodian and his colleagues in several directions as they turned to identify the specific viral types that were infectious. A close colleague, Thomas B. Turner, an infectious disease expert and later dean of the medical school at Hopkins (1957-1968), encouraged them to pursue immunologic studies. They posed the question of whether the disease was caused by a single antigenic type of the virus or by several different immunologic types. At that time the distinction among virus types was best defined by analyzing cross-protection, a highly labor-intensive method. Chimpanzees preinfected with one poliovirus were challenged with another virus strain to determine whether they had acquired immunity that protected against viruses of a different type. All of the 14 strains of poliovirus

then known were compared (later the number of tested strains reached 100). They demonstrated in 1949 that three distinct immunologic viral subtypes could produce paralytic poliomyelitis and concluded that an effective vaccine must be multivalent to protect against all three of the virus types.

## THE TEAM OF BODIAN, HOWE, AND ISABEL MORGAN

Fortuitously, Bodian took a summer trip to Woods Hole and met Isabel Morgan, who was a well-trained and highly capable immunologist. They shared common scientific interests and became good friends. (Isabel was the daughter of Thomas Hunt Morgan, who won the Nobel Prize in 1933 for showing that genes are carried by chromosomes and form the basis of heredity; he graduated from Johns Hopkins University in1891.) Isabel attended Stanford as an undergraduate, wrote her doctoral thesis in bacteriology at the University of Pennsylvania, and joined the Rockefeller Institute for Medical Research, in 1938, to work with Peter Olitsky on immunity to poliovirus. In 1944 David Bodian invited Isabel Morgan to join the polio group at the Johns Hopkins School of Public Health. The research team of Morgan, Bodian, and Howard Howe soon produced a vaccine that protected monkeys against poliomyelitis. They employed poliovirus from nervous tissue of infected monkeys, inactivated it with formaldehyde, and then immunized monkeys with the killed viruses. This finding demonstrated that a vaccine could produce an immune response that protected against poliomyelitis but brought pressure to test the vaccine in children.

Since the virus had been grown in CNS neurons, Morgan was strongly opposed to human testing due to the risk of inducing an antineuronal immune encephalopathy in recipients. At that time, in 1949, she left Johns Hopkins and married Air Force Colonel Joseph Mountain. She stayed in close communication with Bodian and Howe but never returned to polio research. In 1958 she was the only woman among 16 men inducted into the Polio Hall of Fame at Warm Springs, Georgia. In a crucial discovery in 1949 John Enders's group reported that poliomyelitis virus could be grown in tissue culture of non-nervous cells. This was a revolutionary contribution since the virus and vaccine could then be produced without risk of the immune system forming antibodies against neurons.

Bodian continued research on polio over the next 10 years and was joined by Neal Nathanson. Together they confirmed quantitatively that poliovirus viremia could be rapidly terminated by antibody formation. They also documented that virus could enter the CNS by axon transport and could contribute to infection of spinal cord or brain. Transection of the sciatic nerve after virus

injection in the leg blocked infection of spinal motor neurons. A lively race ensued among polio researchers to determine whether a vaccine should be made from killed virus or from a live virus that had been attenuated by serial passage in culture. Development of a killed virus vaccine could be made available sooner and there was great pressure to proceed. Since it was not possible to predict the result, Bodian wisely chose not to intervene in favor of one group or the other.

The first experimental vaccine for human use was made by Salk using formaldehyde-inactivated virus and was approved in 1955 for large-scale production by several drug companies. A fiasco occurred when immunization with the Salk vaccine was followed by a tenfold increase in the rate of polio infection of children. Bodian and Nathanson were instrumental in investigating this problem and showed that six lots of the vaccine made by the Cutter Lab were contaminated with live virus, likely due to their taking shortcuts to facilitate production of the vaccine. Bodian was then invited to join several regulatory committees to set standards and regulate the production of vaccines, a task that occupied much of his time over the next 10 years.

As debate over choice of the vaccine type for humans went on, Sabin was attempting to develop an oral vaccine using an attenuated live virus, and a small field trial on prisoners in 1955 revealed a greatly decreased infection rate. Sabin predicted that a live virus vaccine would induce greater, longer-lasting immunity. The Soviet Union contacted Sabin to request a trial of the Sabin attenuated vaccine. The Soviet government then vaccinated 77 million children and found a huge decrease in the incidence of polio infection. The Sabin oral vaccine was finally tested in the United States in 1960 and approved for general use in 1963 by the Department of Health, Education, and Welfare. Poliomyelitis was almost totally eradicated in the United States within a year, and the Sabin oral vaccine (OPV) soon became the preferred polio vaccine in the United States and many other countries.

Eventually, unexpected and rare problems emerged from use of the oral vaccine. Due to the presence of live virus, the Sabin OPV has the ability to produce a high level of gastrointestinal immunity, and is composed of strains of the three virus types that were attenuated by serial passage in culture. The attenuated strains produce a robust immune response but were not predicted to cause disease since they had lost their pathogenicity. However, in later years the attenuated virus was revealed to be genetically unstable and susceptible to mutation to neurovirulent strains. The U.S. Centers for Disease Control and Prevention estimates that one case of vaccine-induced paralytic poliomyelitis has emerged for every 2 million

doses of oral vaccine administered. While the incidence is small, the risk of introducing infectious poliovirus by vaccination remains. Bodian's last paper on polio (1977), in collaboration with Johns Hopkins Neurology colleagues, reported a fatal case of severe paralytic polio in an immunodeficient child following vaccination with the live virus vaccine. The lack of an immune response in patients with an immune deficiency may lead to a prolonged infection with the attenuated virus for months or years; since the virus can replicate in the absence of antibody, there is an increased chance of mutation to a more virulent form. (In the absence of antibody formation, the attenuated virus continues to replicate and can undergo mutations.) Nathanson states that the overall mutation rate is about 1 percent per year, potentially resulting in 75 mutations per month (based on data from Kew et al., 2005). Although the Sabin OPV has reduced the worldwide incidence of poliomyelitis by 99.9 percent, concern remains about total eradication versus potential reoccurrence of virulent strains. At the time of this writing the U.S. Advisory Committee on Immunization recommends that the oral live attenuated vaccine be discontinued and replaced by the killed virus vaccine; future policy remains to be decided.

Polio research continues to be a timely issue. Up to 2011 sporadic outbreaks of polio infection have appeared in small pockets of the world, particularly in Pakistan, Afghanistan, Somalia, and other parts of Africa (Ethiopia, Nigeria, and Congo). Ten cases recently were reported to spread from Pakistan to China, which had been polio-free for 10 years. China has recently made plans to immunize more than 8 million people over several weeks. The World Health Organization and the Gates Foundation have announced funding for a new research effort to eradicate poliomyelitis from the world. Despite great progress a question remains as to which vaccine should be used in the future since the attenuated virus vaccine (Sabin OPV) can mutate back to a virulent virus.

## DAVID BODIAN'S LATER CAREER

In 1957 Johns Hopkins University appointed Bodian professor and chair of anatomy in the School of Medicine, where he conducted active research until 1977 when he became professor emeritus in the Department of Laryngology and Otology. He continued to make important contributions both in research and teaching. Despite the administrative burden of chairing a medical school department, he remained a hands-on bench researcher. I often enjoyed chatting with him in the corridor while he waited to dark-adapt to wearing goggles in preparation for studying synapses by electron microscopy. He was happy to put the polio arena aside and get back to more basic research on synaptic connections in the CNS. His organizational skills and leadership led to reorganization of the anatomy department and

the development of teaching programs in neuroanatomy, cell biology, and gross anatomy. He always showed a philosophic bent toward biology, and published several papers on the functional organization of neurons as related to morphology. One of his influential papers of this type was "The Generalized Vertebrate Neuron" (1962) in which he classified neurons and sensory receptors based on the site of impulse initiation. He emphasized that in sensory receptor neurons the site where impulses arise lies in the most distal part of the axon, but is located in the axon hillock of motor neurons and most central neurons. That distinction remains widely taught and has simplified the understanding of neuronal function.

Bodian continued hands-on productive research over many decades. He was excited by the availability of the electron microscope and spent much time evaluating the morphology of synapses at high resolution. He analyzed and published the morphology of spinal cord synapses. Among his novel discoveries was the recognition that synaptic vesicles differ in shape such that spherical vesicles are associated with excitatory synapses while ovoid vesicles are largely found in inhibitory synapses. He also performed electron microscopy (EM) experiments to determine the organization of the neurohypophysis and the modes of hormone secretion by the pituitary gland. The next area that engaged him was synaptic development in spinal cord of fetal monkeys where he studied the association of fetal reflexes with the formation of particular synapses, reported in papers from 1966 to 1971. Following his retirement as Anatomy chair, he joined the Department of Otolaryngology, where he had a new, modern EM laboratory to analyze synapses in the cochlea (the organ of Corti) over the next five years.

From 1960 to 1973 Bodian was actively involved in medical school teaching, especially in neuroanatomy, where he frequently lectured and taught in the laboratory sessions in addition to producing a superb collection of microscopic slides and brain sections for the students. After directing the neuroanatomy course for many years, he joined with his close friend Vernon Mountcastle and together they developed a course that combined neuroanatomy with neurophysiology. Eventually they were joined by Sol Snyder and added neuropharmacology; all areas of neuroscience were brought together to present a new course covering neuroscience. Enthusiastic faculty members working together in that course led to new and effective research collaborations, and the departments were merged into the Department of Neuroscience with Solomon Snyder as director.

## SOME PERSONAL NOTES

Shortly after joining the Johns Hopkins faculty in 1942, David Bodian met Elinor Widmont, an artist in the Hopkins Department of Art as Applied to Medicine

and they married in 1944. They were dedicated to their three daughters and two sons: Brenda, Helen, Marion, Alexander, and Marc. Elinor was both an abstract artist and medical illustrator, and they enjoyed a happy, productive life together for 48 years. They frequently collaborated, and Elinor created superb drawings to illustrate his publications. The Bodian family lived in a large, modest rural house north of Baltimore, where colleagues gathered on many weekends. The family also enjoyed spending summers at their vacation house in Woods Hole, where they had frequent contacts with scientific friends at the Marine Biological Laboratory.

Bust of David Bodian from Polio Hall of Fame.

Photo by Henry Lytton Cobbold

Bodian will be missed and remembered as a friend and scientific colleague. He was always smiling, witty, friendly, and well known for his modesty, integrity, and collaborative spirit. He was a dedicated teacher and often spoke of the role of the university in teaching and supporting innovative new research at the frontiers of science. He strongly advocated that the university be responsible for preserving older knowledge and not abandoning it for the most current trends.

His modesty and collaborative spirit are displayed in his tribute (Bodian, 1957) to Basil O'Connor at a meeting to celebrate advances in polio research.

> The National Foundation for Infantile Paralysis under dedicated, imaginative and decisive leadership has elevated the role of publicly supported agencies from that of patrons of the sciences to one of direct partnership with scientists. The role of partnership involves an exchange of understanding and mutual stimulation leading to the vital…bridge between humanitarian goals and the world of research. We owe a personal debt of gratitude to Basil O'Connor because his example has taught us to work within this framework of responsibility for shared objectives without sacrificing personal goals of creative effort in research.

## SUMMARY

David Bodian's life exemplifies several important concepts related to scientific progress. His humility and efforts to collaborate with other colleagues set a positive example. The story of polio as told by Oshinsky reveals the intense competitiveness and self-interest expressed by some of the participants. Competition certainly plays a positive role in making progress, but ultimate success depends on collaboration and the sharing of ideas. Bodian with his collaborators planned experiments and collected data that eventually led to understanding poliovirus entry, spread, and pathology. He was outspoken in support of collaborative effort. His laboratory demonstrated that a vaccine can induce antibodies that arrest the progress of the disease. Most of this work was done before the advent of modern immunology, which much later provided molecular methods to identify the polio receptor. The receptor for poliovirus, CD155, is one of several immunoglobulin-like proteins in the cell

membrane that bind to the dynein complex and provide a mechanism for virus uptake and retrograde axonal transport to the cell body through microtubules. Later CD4 was found to be the receptor for HIV, another member of this family. Neurotropic viruses such as poliovirus, HIV, herpes virus, rabies virus, and pseudorabies can be taken up by corresponding receptors and invade the central nervous system by retrograde axonal transport. This story confirms that financial support for basic research is crucial to enhance medical progress and will provide new basic tools that facilitate treatment and prevention of other diseases.

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