Caisson disease during the construction of the Eads and Brooklyn Bridges: A review.

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Butler WP. Caisson Disease during the construction of the Eads and Brooklyn Bridges. Undersea Hyperb Med 2004; 31(4):445-459. The Eads Bridge (St. Louis) and the Brooklyn Bridge (New York City) were testing grounds for caisson construction. These caissons were enormous compressed air boxes used to build riverine piers and abutments anchoring the bridges. Caisson meant faster and cheaper construction, but there was a hidden cost---caisson disease (decompression sickness). Within caissons, workers labored at pressures as high as 55 psig and caisson disease was common. This discourse is a brief history of the caisson, a brief discussion of the illness as viewed in the mid 1800's, and an abbreviated history of the Eads and Brooklyn Bridges. It also provides a detailed description and evaluation of the observations, countermeasures, and recommendations of Dr. Alphonse Jaminet, the Eads Bridge physician, and Dr. Andrew Smith, the Brooklyn Bridge physician, who published reports of their experience in 1871 and 1873, respectively. These and other primary sources permit a detailed examination of early caisson disease and Jaminet's and Smith's thinking also serve as good examples from which to study and learn.

The history of the United States is replete with examples of monumental construction projects: the Hoover Dam, the Empire State Building, and the Transcontinental Railroad to name but a few. Seldom, however, have any of these projects had a direct impact on the practice of or the thinking in medicine. There are exceptions and this discourse is an account of two---the Eads Bridge spanning the Mississippi River in St. Louis and the Brooklyn Bridge spanning the East River in New York City. Both projects were *avant garde* and thought by many to be pipe-dreams. Both projects were begun and completed in the 1870s. And, both projects used the relatively new caisson construction technology.

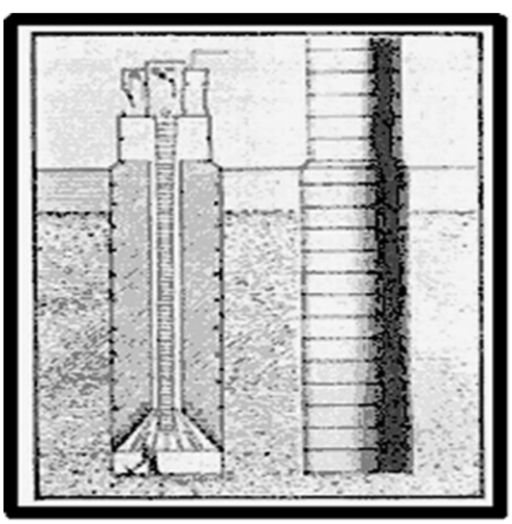


Fig. 1. The pneumatic caisson of Triger.(from Hill, Caisson Disease; London: Edward Arnold; 1912)

Caisson construction was initiated in 1839 by a French mining engineer named Triger. To bridge a stretch of quicksand and access a rich vein of coal he constructed a metal tube positioned within the mine shaft. He then applied compressed air to the tube; this pressure pushed watery sand from the metal shaft allowing the coal to be mined. Of note, this tube was seventy feet long and three-and-a-half feet in diameter; it had a surface-placed "pressure box" (now, referred to as an air-lock; see Figure 1) for the workers to enter and exit the pressurized tube (1).

Although the original caisson idea probably dates to 1691 with Papin, was elaborated by Coulomb in 1779, and certainly patented by Cochrane in 1830, it was Triger who first employed it (1). And, it was Triger who first described physical effects associated with the elevated atmospheric pressures.

Triger made five observations: there was no whistling at three atmospheres [1 atmosphere (atm) = 33 feet sea water (fsw) = 14.7 pounds per square inch (psi)]; there was a nasal tone to the voice; at depth, a deaf miner was better able to hear than normal miners; miners climbed steps better in compressed air; and, two miners had joint pains (one had left arm pain and the other had left shoulder and bilateral knee pain) (4). It was in 1854 that physicians first published any notes. Pol and Watelle described the medical problems encountered within the Douchy mines (France). Of 64 miners, forty-seven endured the work relatively well, twenty-five abandoned the work, and two died. They noted, "The danger is *not* in going into the compressed air. It is not a disadvantage to stop there a longer or shorter time. The decompression only is to be feared. *One only pays on coming out*."(5) Indeed, this was a telling observation, for both the Eads and Brooklyn Bridges were plagued with decompression sickness. This article reviews those problems and the countermeasures employed by each project's physician.

Caisson Disease

"Caisson Disease" is a term coined by Andrew Smith to describe the illness that he encountered among workers during the construction of the Brooklyn Bridge (6). Although it is more commonly called decompression sickness (DCS) today, caisson disease remains a popular colloquialism. It is generally employed to differentiate the industrial/construction decompression sickness from the diving and altitude DCS. Examples include mining, tunnelling, and bridge-building.

Regardless of the name, the disease remains the same. It is "too much nitrogen disease." Normally, tissues at a constant pressure are saturated with a certain amount of dissolved inert nitrogen. If ambient pressure drops, there is a concomitant fall in the nitrogen pressure. Dysequilibrium ensues and tissue supersaturation takes place. As a result, the tissues tend to release "excess" nitrogen to the vascular system for delivery to the lungs where it is exhaled into the atmosphere. Thus, a new equilibrium is established. Unfortunately, the change in pressure can exceed the body's capability to release the extra nitrogen. Once a critical point is reached the nitrogen can no longer remain dissolved and bubbles form. These bubbles may develop in the tissues themselves or in the vasculature or, for that matter, may simply grow from circulating micronuclei (microbubbles) already present. In any event, the myriad of symptoms caused by these bubbles define decompression sickness.

Decompression sickness has been clinically typified for over 150 years. Initial reports of decompression sickness came from the industrial/construction world followed by the diving world, and, finally, the aviation world. In 1960, the Decompression Panel of the Medical Research Council adopted the now familiar Type I and Type II DCS (7). Type I DCS can be thought of as "non-serious" decompression sickness. It is most commonly manifest with joint ("bends") and skin symptoms. Interestingly, the term "bends" is a contraction of Grecian Bend. In the 1870s a popular ladies' fashion produced a distinctive forward bent posture known as the Grecian Bend. When compressed air workers suffered joint pains their posture mimicked the "Grecian Bend." Workers, chiding their peers, eventually shortened it to "the bends." Interestingly, this euphemism has variously been attributed to either the Eads Bridge or Brooklyn Bridge workers (8,9,10,11). On the other hand, Type II DCS is "serious" decompression sickness. Manifestations include pulmonary ("chokes"), vestibular ("staggers"), and neurologic symptoms. Unchecked, progression to cardiovascular collapse and death can happen. Of note, Neumann and Bove suggested a diving-associated Type III DCS in 1987 (12) characterized by progressive and treatment-resistant decompression sickness. Here, an exposure loading great amounts of nitrogen (without DCS symptoms) is associated with arterial gas bubbles that serve as a nidus for this malignant and often fatal form of decompression sickness.

Unfortunately, the universal acceptance of bubble evolution has been achieved only in the last eighty odd years. This situation was singularly true with altitude DCS. In fact, Corning's suggestion in 1890 that altitude symptoms were analogous to caisson symptoms was largely ignored until 1917 when Yandell Henderson popularized the concept of altitude DCS (13,14).

It is little wonder that the etiology of decompression sickness was unknown during the mid-1800s. At that time a number of mechanisms were suggested: "vitiated air," anatomic alteration, and "apoplectic hemorrhage" are but a few (15). However, there were three major hypotheses under discussion.

The first was systemic exhaustion. Here, compressed air provided super-levels of oxygen causing extra metabolism and excess waste overtaxing normal physiologic function. Thus, the cold from decompression coupled with the fatigue occasioned by compression led to exhaustion (1,15,16). Indeed, Jaminet notes that "exhaustion of the system…has been…with a very few exceptions, the cause of what has been called 'bridge cases'."(16) There were few proponents of this notion.

The second hypothesis, which was more popular, was systemic congestion. Here, the compressed air forced the circulation from the periphery to concentrate and stagnate in the internal organs producing malfunction (3,6,15). Indeed, Smith articulated the "laws" particularly well: "…under high atmospheric pressure the centres will be congested at the expense of the periphery…firm and compact structures will be congested at the expense of those more compressible…structures within closed bony cavities are congested at the expense of all others..."(6). Other supporters of this hypothesis were Corning, Von Rennselaer, Hunter, and Moxon(13,17,18,19).

The third hypothesis was tissue/vascular bubbles. This notion arose in 1670 when Boyle observed a bubble in the aqueous humor of a snake and was further refined when Hoppe, in a remarkable series of animal experiments in 1857, demonstrated intravascular free air with rapid decompression to altitude (43,000 to 66,000 feet)(20). Clearly, this was the first demonstration of altitude decompression sickness. Indeed, he took these observations farther, "if, after submitting an animal to compressed air for some time, one suddenly diminishes the pressure, there will not be time for the gas to escape from the venous blood in the lungs. This is why in the mines of France, sudden deaths have taken place, and no anatomical lesions have been found."(20) Francois, Panum, and Mericourt published supporting reports (21,22,23). In fact, Mericourt is probably the source for the most popular of teaching analogies: "The greater the depth and the longer the stay at the bottom, the more will the blood be charged with an excess of gas in solution. The diver is really, from a physical point of view, in a condition like to a bottle of water charged with carbonic acid." (23) Later, in 1878, Paul Bert published his classic treatise, La Pression Barometrique, which definitively proved the bubble hypothesis (2). Despite this publication the congestion theory continued to receive support. In the midst of this controversy, the Eads and Brooklyn Bridges were built. The physicians attached to each construction project not only published their observations, but also became vocal proponents of the exhaustion theory (Jaminet) and the congestion theory (Smith).

History of the Two Bridges

Triger's new caisson technology spawned rapid application. Blavier used it to mine Douchy and Bouhy used it to mine Strepy-Bracquegnies(24,25). It came next to bridge-building, where the caisson was an ideal technology for constructing the heavy piers upon which a bridge would rest. A large box was constructed within which the pier would be built. The walls and roof were reinforced; however, there was no floor. The box was then floated into place; construction of the pier's shell added an ever-increasing weight. As the shell became heavier the caisson gradually dropped into the river until it reached the river-bed. Compressed air was then pumped into the caisson and river water driven from the caisson. Now, a space was available for the workers to dig and remove earth. At the same time construction of the pier continued above. This above and below work proceeded until bedrock was encountered. Having attained bedrock the pier could then be anchored to it and the workers' space filled with concrete. This advance proved much cheaper and much faster than the cofferdam (a large fabricated metal oval dam designed to hold back the river's waters during pier construction)(10,15).

Bridge caissons made their first appearance in England. The British engineers, Wright and Hughes, are credited with the first bridge caisson. They employed caissons to span the Medway River at the city of Rochester. The greatest depth attained was 61 feet at 27 psig. Hughes described ear pain, heartier appetites, and minor changes in respiratory rate and depth; however, no cases of DCS or deaths were reported (26). Shortly thereafter, in 1859, the first death was recorded at Saltash; all 25 workers suffered DCS, two with paraplegia, one hemiplegia, and one coma (27). Unfortunately, morbidity and mortality were not extraordinary in compressed air work. As the caisson became more common, medical problems became more common (Table 1).

This technology was not ignored in the United States. Apparently, the first bridge built with caisson construction crossed the Pee Dee River in South Carolina. Although most likely erected in the 1860s, no confirming records are readily available (3). However, the next two bridging projects were monumental in both scope and documentation. In fact, each project engaged a physician to oversee the caisson work. Of note, each physician dutifully published his experiences and observations---Dr. Alphonse Jaminet of the Eads Bridge and Dr. Andrew Smith of the Brooklyn Bridge (6,16).

Table 1. Compressed Air Casualties in Early Bridge-Building

TABLE I

Compressed Air Casualties in Early Bridge-Building*

Year	Bridge	River	Country	Depth (feet)	Illness	Mortality	Informant
1851	Rochester	Medway	England	61		0	Wright/Hughes
1851	Chepstow	Wye	England			0	Brunel
1856	Szegedin	Theiss	Hungary	65.6			Cezanne
1859	Saltash	Tamar	England	87.5	25	1	Brunel/Littleton
1859	Bordeaux	Garonne	France	42.3		0	Regnauld
1859	Kehl	Rhine	Germany	82.5	133	1	Francois
1859	Kaffre-Azzyat	Nile	Egypt	85		5	London Times
1861	Argenteuil	Seine	France				Foley
1862	Bayonne	Adour	France	82.5	90%	1	Limousin
1863	Londonderry	Foyle	England	75	many	4	Babington/Cuthbert
1869	Vichy	Allier	France				Moreaux
		Pee Dee	USA				
1870	St. Louis	Mississippi	USA	127	119	14	Jaminet/Woodward
1873	Brooklyn	East	USA	77	110	3	Smith

*from Littleton (1855), Babington/Cuthbert (1863), Woodward (1881), Snell (1896), Hill (1912), McCullough (1972)

The Eads Bridge---completed 1874

In the early 19th century Mississippi paddle-wheelers dominated mid-western trade. St. Louis was the key port of call. By the 1870s the steamboat no longer predominated; railroad was king and Chicago was pre-eminent. To remedy the situation, the St. Louis and Illinois Bridge Company was formed in 1864 and a bridge over the Mississippi River at St. Louis was envisioned (8,10). After reviewing a number of plans the company accepted the controversial drawings of James Eads. Soon after its completion this monumental bridge took his name.

Eads was the archetypal self-made man. He had designed a diving bell and had become quite wealthy salvaging many a Mississippi wreck. He knew the river-bed as no other man of his time. Although no engineer, he was inventive and technologically astute with a unique ability to make things happen. His design called for three massive cantilevered arches spanning the river. To anchor these arches he proposed building the supporting piers on river-bed bedrock. Importantly, the two mid-river piers were covered by an intimidating 25 feet of water and 80 feet of sand. Nothing of this magnitude had ever been attempted (10).

Originally, he planned to use cofferdams to construct his massive piers. In fact, the shallower west abutment was built in just this way. However, it required only a mere 47 feet of digging. Subsequent to this success, while travelling in Europe (early 1869) he encountered the compressed air caissons of Hughes in England and Moreaux in France. Eads was not only impressed, but he was also convinced that the caisson was the best approach for building the mid-river piers and east abutment (8,10,29).

Construction of the east mid-river caisson began during the spring of 1869. It was an irregular hexagon with two 52 foot sides and four 33 foot sides; overall, it encompassed an area of 82 feet by 60 feet. There were seven air locks positioned just above the worksite as well as a steep staircase connecting the worksite to the caisson surface (Figure 2).

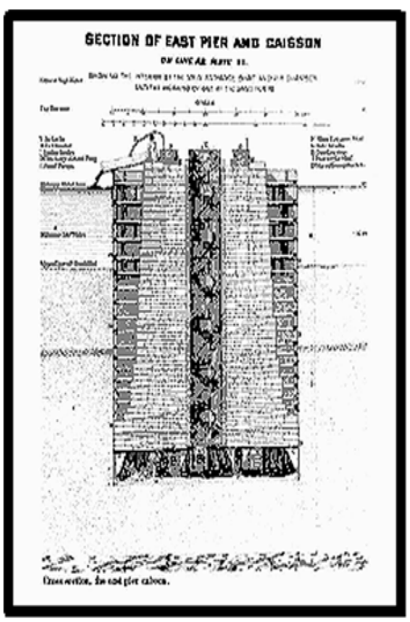


Fig. 2. The Eads Bridge Caisson. Cross section of East Pier and Caisson showing air chamber and working of a sand pump. (from Woodward, A History of the St. Louis Bridge; St. Louis: GI Jones and Company; 1881)

By mid-October the caisson was ready. It was towed into place and gradually sunk until resting on river bottom. Work began around the clock. About thirty men laboured at any one time within the caisson. In January 1870 the smaller west mid-river caisson was launched, measuring 82 feet by 42 feet with only five airlocks. When the eastern caisson touched bedrock in February the worksite was 95 feet below the river at 45 psig. Indeed, the east caisson's maximum pressure was 52 psig and the west caisson's was 40 psig. Subsequent to their completion in late May, work began on the east abutment caisson. This proved just as difficult with a maximum depth of 127 feet (~55 psig). Work on all four mighty anchors finally ended in March of 1871 (10,16).

Unfortunately, problems quickly surfaced. At 25 psig (~55 feet below the river's surface) men began to notice a variety of joint pains. As the east caisson settled deeper into the river ever increasing episodes of paralysis appeared: "The first effect upon the men was an occasional muscular paralysis of the lower limbs. This was rarely accompanied with pain, and usually passed off in a day or two." (29) Eads made the decision to send affected men to the St. Louis City Hospital on 15 February 1870; the caisson was 76 feet deep at 35 psig. On 19 March, James Riley completed a two-hour shift only to collapse dead fifteen minutes later. That same day another man died. And, three days later twenty "bridge cases" were sent to the hospital; five died (9,16,29). The situation was desperate.

Alphonse Jaminet, Eads personal physician and friend, was engaged on 31 March 1870. Up to that time there had been several dozen serious cases and eleven deaths (five months). It was Jaminet's task to interrupt this epidemic. During his fourteen-month tenure he attended seventy-seven cases. Of course, these cases were the serious ones; less severe episodes most certainly went unreported. The average age was 27 years with just under two months work experience and almost three-quarters of the cases happened at the second watch (each shift was composed of a variable number of watches, or work periods, dependent on caisson pressure). The mean caisson pressure was 44 psig (99 feet). Most presented in less than 30 minutes and resolved within 15 hours. Epigastric and back pain were common; bladder and bowel dysfunction were not infrequent. Seventy-one were neurological: a full fifty-seven had spinal DCS; only three persisted with permanent residua (paresis requiring two canes, paraplegia, and generalized weakness) (16,29). Tragically, three men died---two from complications of paraplegia (extensive bedsores with a subsequent pulmonary embolus) and one within three hours of unconsciousness (autopsy revealed "…the brain was congested (and) all the membranes covering the brain were highly congested…") (16). See Table 2.

Table 2. Eads Bridge---Caisson Disease (Jaminet)

TABLE II

Eads Bridge --- Caisson Disease (Jaminet)*

Presenting Sxm	Cases (n = 77)	Avg Time to Sxm (minutes)	Avg Resolution Time (hours)	Other Symptoms			
				epigastric pain	joint pain	back pain	bladder dys
Epigastric Pain	2	25	9 (n = 2)				
Joint Pain	4	14	14 (n = 3)	4			1
Neurologic	71	16	11 (n = 59)	64	25	24	7
Cerebral	14	2	11 (N = 11)	13			
Spinal	57	19	10 (n = 50)	51	25	24	7
> paraplegia	9	26	10 (n = 5)	9	2	3	4
> paraplegia & arm	2	12		2	1		2
> paresis	37	19	11 (n = 32)	34	22	21	
> parapsis	8	17	14 (n = 7)	6			
> general paralysis	1	0					1

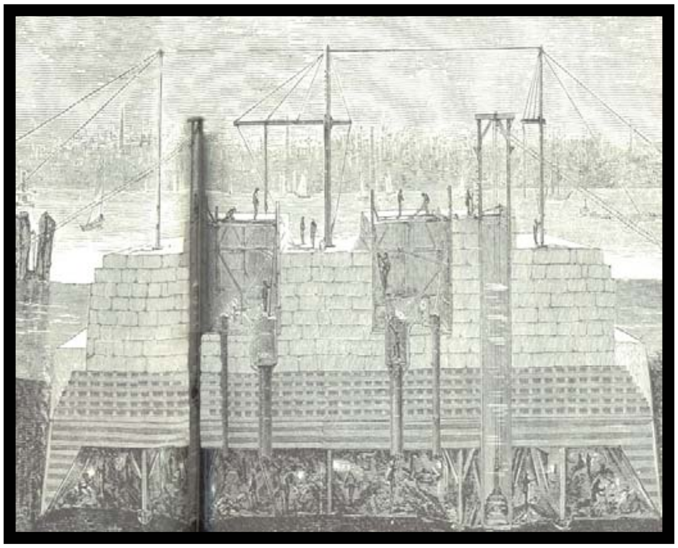
The Brooklyn Bridge---completed 1879

The original plans for the Brooklyn Bridge were devised by Charles Ellet and John Roebling during the 1850s. A number of years later, Roebling completely revised the plans and, shortly thereafter, they were accepted for the East River project. Unfortunately, the task fell to Washington Roebling when his father died (8).

Unlike the Eads Bridge, caissons had been considered essential from the very start. Unlike James Eads, both Roeblings had studied caisson design and implementation extensively. Not unlike the Eads Bridge, however, the Brooklyn Bridge encountered serious caisson disease. Of note, both the Eads and Brooklyn Bridge caissons were larger than their European counterparts and the rivers were much deeper and much more treacherous (8).

In May 1870, work began on the Brooklyn side (Figure 3). There were three shifts daily over a six-day work week. Each shift was eight hours. The two daylight shifts were manned with 112 men each and the night shift was manned with 40 men. From start to finish the Brooklyn caisson employed some 2,500 different workers. Needless to say, there was a severe turnover. This resulted from the miserable conditions. The caisson was hot and humid with standing puddles of water and waste; early on there was no toilet. Despite these problems, the work progressed and the caisson gradually settled onto the river floor. The final depth was about 45 feet and the greatest pressure experienced was 21 psig. Only three or four workers suffered a very mild transient leg paralysis (6,8).

Fig. 3. The Brooklyn Bridge Caisson. Cross section demonstrating work above and below the water's surface. (from Conant, WH. The Brooklyn Bridge. *Harper's New Monthly Magazine*. 1881; 66(396):925-946)



The New York caisson, begun in September 1871, was not as fortunate. This caisson was larger by four feet at 102 ft x 172 ft and penetrated much deeper. Early on the work was much easier. There were no huge boulders as had been encountered on the Brooklyn side. As a result, the caisson sank quickly. Within six weeks the caisson was at 51 feet (24 psig). Men began to report "….a good deal of discomfort…(to)…severe pain (8)." Roebling aware of Eads' problems decided an on-site physician was necessary (6,8).

Andrew Smith, a throat specialist, was commissioned; his tenure ran from 25 January to 31 May 1872. During this time he diagnosed and treated 110 cases of caisson disease. Doubtless, many, many cases went unreported and, despite his best efforts to tame the disease, it did not disappear. In his 1873 essay, Smith details twenty-four cases. The average age was 39 years with just under one month of work experience and almost two-thirds of the cases happened at the second watch. The mean caisson pressure was 30 psig (69 feet). Most presented in less than 60 minutes and resolved within 1-3 days. Epigastric pain and bladder dysfunction were not infrequent. Thirteen had neurological symptoms, eleven referable to the spinal cord; yet, there were no documented permanent residua (6). See Table 3.

TABLE III

Brooklyn Bridge --- Caisson Disease (Smith)*

Presenting Sxm	Cases (n = 24)	Avg Time to Sxm (minutes)	Avg Resolution Time (hours)	Other Symptoms					Deaths
				epigastric pain	joint pain	back pain	bladder dys	bowel dys	
Epigastric Pain	1	0							
Joint Pain	10	15 (n = 8)	106 (n = 3)	1				1	
Chokes	1	60							1
Neurologic	12	8 (n = 10)	63 (n = 7)	5	5	1	3	1	2
Cerebral	2		72 (n = 1)		1				1
Spinal	10	9 (n = 8)	62 (n = 6)	5	4	1	3	1	1
> paraplegia	4	8	91 (n = 3)	3	3	1	1	1	1
> paraplegia & arm	2	23	2 (n = 1)	1	1				
> paresis	2		24						
> unknown	2	0	48 (n = 1)	1			2		

*from Smith (1873)

Table 3. Brooklyn Bridge---Caisson Disease (Smith)

At 33 psig (~75 feet) bedrock was first encountered; however, at 34 psig, two fatalities occurred. The first was a "corpulent" fellow who upon leaving the caisson was immediately seized with severe epigastric pain followed by bilateral leg pains; paralysis quickly followed. In less than 24 hours, he was dead. Autopsy found an "intensely congested" cord with "an extensive effusion of blood pressing upon the cord." The next man was found in the lock; he was unconscious with a "…pulse irregular and feeble." Shortly thereafter, he awakened only to lapse into "paroxysms of convulsions." He was dead in nine hours. Autopsy was remarkable only for Bright's Disease. And, at 35 psig, there was a third and final fatality. This "stout, heavy" man began feeling ill about an hour after exiting the caisson. He never reached home; he was discovered on the boarding house stairwell dead. His lungs "…were congested to a very remarkable degree (6)." Washington Roebling, himself a serious victim of caisson disease, decided to call a halt to work that very day. He decided to rest his reputation, his career, and his bridge on a spit of sand rather than bedrock (8). Today, the Brooklyn Bridge remains a reaffirming testament to that wisdom.

Jaminet and Smith

To mitigate caisson disease both Jaminet and Smith attacked from a pathophysiologic perspective. Smith believed caisson disease the result of systemic congestion. He was greatly impressed with autopsy evidence: "The constant lesion in fatal cases of caisson disease is congestion of the brain and spinal cord (6)." In contrast, Jaminet firmly believed the problem stemmed from complete exhaustion of the system with an excess build-up of waste. This belief was rooted in his own personal experience. Prior to being commissioned he had made a number of forays into the caisson to conduct experiments. On one such occasion, after almost three hours at 45 psig, he decompressed the full 95 feet in less than four minutes. He then climbed the caisson staircase. Within forty-five minutes he was paralyzed. Over the ensuing week he gradually returned to normal. Early on, he realized that any movement not only sent piercing pain throughout his limbs, but also exacerbated his paralysis. And, during his recovery he noted how feeble he had become (16). To be sure, this frightening experience affected his views.

Despite the theoretical differences both Jaminet and Smith wrought similar countermeasures. An easy way to examine their actions is by the tripartite prevention model. Primary prevention methods avoid the problem altogether. Secondary prevention methods separate "susceptibles" from the problem. And, tertiary prevention methods minimize the effects of the problem. These interventions, unfortunately, do not eliminate hazard, they only mitigate risk. Both Jaminet and Smith reported this fact. Table 4 summarizes their countermeasures.

The first step, **primary prevention,** was workplace re-engineering. Both physicians felt that exertion after exposure held great import. Both sought to increase and enforce rest between and after shifts. Jaminet had a floating room for rest constructed where workers would rest at least one hour after work while drinking three-quarters of a pint of strong beef tea. He also insisted they eat their dinner during this rest time (16). Similarly, Smith had a yard room built filled with bunks, benches, and hot/cold bathing facilities. Here, workers could rest, drink company-brewed hot coffee, and change into dry underclothing (6).

Along these same lines, both observed cases associated with stair climbing. Smith best expressed the problem: "As at the moment of going out of the compressed air the system undergoes a violent reaction, it is manifestly unfitted to bear in addition a severe tax upon the muscular strength. Hence, the ascent of a long flight of stairs, immediately after leaving the air-lock, is as wrong in theory as it has proved bad in practice (6)." As a result, both lobbied for and won elevators for the workers.

Table 4. Prevention Methods

TABLE IV		
Prevention Methods*		
	Jaminet	Smith
Primary		
work schedule	based on depth & very detailed	based on depth & basic
post-exposure exertion	floating room for rest	yard room for rest
	elevator installed, avoid stairs	elevator installed, avoid stairs
locking procedures		
compression	3 psi/min	3 psi/min
decompression	6 psi/min	5 psi/min
new worker	no program	gradual introduction to pressure
Secondary		
worker fitness	pre-placement & periodic exams	pre-placement & periodic exams
Tertiary		
treatment facility	floating hospital	yard hospital
treatment	bedrest, beef tea, cordial (rum)	morphine, atropine, ergot
Recommendations		
	none	workers' barracks
		medical lock
		***from Jaminet (1871) & Smith (1873)**

Furthermore, both doctors regularly sought to reduce pressure exposure. Jaminet elaborated a detailed shift (work-rest cycle) regimen based on caisson pressure. This was the consequence of variously tried schemes. It is as follows (16):

pressure (psig)	watch (hr)	surface rest (hr)	watch (hr)	surface rest (hr)	watch (hr)	day end rest (hr)
15-20	2	2	2	2	2	
20-25	2	3	2	3	2	
25-30	2	3	2			1
30-35	2	4	2			1
35-40	1	2	1	2	1	1
40-45	1	4	1			1
45-50	1	6	1			1
50-55	1					

Since the pressures in New York did not reach the levels of St. Louis (35 psig versus 55 psig), Smith's regimen was much more basic. He reasoned that a worker's hours should drop systematically as the pressure rises: 0 psig = 12 hours, 15 psig = 6 hours, 30 psig = 4 hours, 45 psig = 3 hours. To that end, a 4 hr work x 2 hr rest x 4 hr work shift eventually became a 2 hr work x 4 hr rest x 2 hr work shift (6). Of note, both recognized the new worker was at increased risk, but only Smith actively intervened with a graduated introduction to the work. Simply put, one watch could be worked the first week, one and a half the second week, and a full shift the third week.

Each physician focused attention on the locking procedures. Jaminet declared "…most important of all…is the duration of time to remain in the air-lock when going into the caisson or air-chambers…and when coming out to return into the normal atmosphere…"(16) Likewise, Smith believed "…the one essential cause, without which the disease can never be developed, is *the transition to the normal atmospheric pressure, after a prolonged sojourn in a highly condensed atmosphere* …Perhaps the most frequent exciting cause of the Caisson Disease is *too rapid locking out*. Indeed, it is altogether probable that if *sufficient time* were allowed for passing through the lock, the disease would never occur (6)." No longer was "open valve" compression-decompression permitted. For example, open valve decompression was the common practice of simply opening the valve wide to allow as rapid a return to atmospheric pressure as possible. This technique often provoked an immediate case of caisson disease. Jaminet and Smith both insisted compression proceed not faster than 3 psig per minute and decompression not exceed 5-6 psig per minute (6,16).

Secondary prevention was directed at worker fitness. Both doctors promoted proper diet (three daily meals) and regular sleep along with temperance in both alcohol and tobacco. Since many of the men lived in crowded tenements, Smith even advocated an on-site workers' barracks where they could eat and sleep in a clean, restful environment. The cost would be garnished from wages (6). Needless to say, this was never instituted. Both advised against hiring overweight workers. Indeed, analyzing Smith's data demonstrates a significantly greater risk of paralysis or death in heavy workers as opposed to those with medium or spare builds (Odds Ratio > 4; chi square p value < 0.05).

Pre-placement and periodic exams became the norm. Workers were screened both medically and physically to ensure their ability to tolerate the elevated pressures. Each physician excluded workers with heart or lung disease. Jaminet did not allow workers over 45 years old and Smith did not allow workers over 50 years. Smith rejected but a few workers; however, "…the knowledge that they would be examined, doubtless deterred many who were not sound…"(6) On the other hand, Jaminet rejected many. In February 1871, 133 men sought work. He found 67 unfit---general debility from intemperance (25), chills within the prior two weeks (11), over 45 years old (8), general debility from illness (7), consumption (6), large leg ulcers (5), epilepsy (3), and heart disease (2). In addition, Jaminet held a muster roll every day examining workers for fitness. Those he found temporarily unfit, he re-examined twice daily until again fit (16).

Tertiary prevention was considerably lacking. Workers used voltaic devices (belts, wrist bands), patent liniments (Magic Oil, King of Pains), and hot baths to no avail. Jaminet and Smith noted hot baths temporarily relieved pain, but were swiftly followed by paralysis. Consequently, they roundly condemned them (6,16).

Both physicians saw the need for and ensured an on-site hospital was constructed. However, their treatments failed to intervene; they merely supported. Sadly, both were overly influenced by their personal experience. Jaminet knew caisson disease personally; he felt the pathology to be exhaustion. As a result, he treated with large doses of rest and liberal use of beef tea. Many, especially those with epigastric pains, were regularly dosed with a cordial (spiritus Jamaicensis, syrupus simplex, oleum anisi). Pain was treated with ice, bladder paralysis with catheterization, and bowel dysfunction with quinine, rhubarb extract, and assafaedita-based enemas (16). In contrast, Smith felt the disease came from vascular congestion; he used the vasoactive ergot. He reasoned that ergot would contract brain and spinal cord vessels reversing the congested state. He treated pain with morphine and atropine. And, he attacked paralysis with cold douches/frictions to the spine, dry cups/leeches, and strychnine in prolonged cases (6).

These less than adequate countermeasures have garnered rather severe criticism. In fact, both men have been roundly condemned for ignoring European science (8,10,15). Jaminet in St. Louis probably did not have access to French and German literature and probably could not have translated German. Smith was well aware of European science and completely eschewed it until his final recommendation; whereupon, he manifestly supported incorporating a medical lock for treatments (6).

In reality, do these men deserve such criticism? Probably not. Examining their results is illuminating. The one clear measure of their interventions is mortality. During the five months before Jaminet was engaged there were eleven deaths and "several dozen" severe cases; this at a pressure in and around 35 psig (16,34). In fact, Diaz suggests the several dozen cases might well be forty-five (10). These numbers are probably representative of the baseline problem---2.2 deaths per month for a case fatality rate of ~24%.

During Smith's five-month tenure, pressures did not exceed 35 psig. He attended 110 cases with three deaths averaging 0.6 deaths per month for a case fatality rate of ~3%. Assuming the pre-Jaminet experience in St. Louis a pretty good estimate of baseline and assuming the "several dozen" cases to be around 45, did Smith do a good job? The odds of surviving on Smith's regimen was about eight-fold higher than baseline (chi square p value = 0.001). So, it would seem Dr. Smith did a very good job.

Now, turn to Jaminet, who has received the harshest of criticism. He encountered 3 deaths and 74 severe cases during his fourteen-month tenure averaging 0.2 deaths per month for a case fatality rate of ~4%. This is comparable to Dr. Smith. In perspective, much of his time was spent fighting pressures in excess of 35 psig and as high as 55 psig. Let's use the same assumptions. The odds of surviving on Jaminet's regimen was a little over six times higher than baseline (chi square p value = 0.006). So, it would seem Dr. Jaminet also did a very good job. In fact, despite the higher pressures and presumably greater risk in St. Louis, there appears to be no difference in case fatality rate between Jaminet and Smith (chi square p value = 0.693). Clearly, both physicians created a safer workplace for the workers.

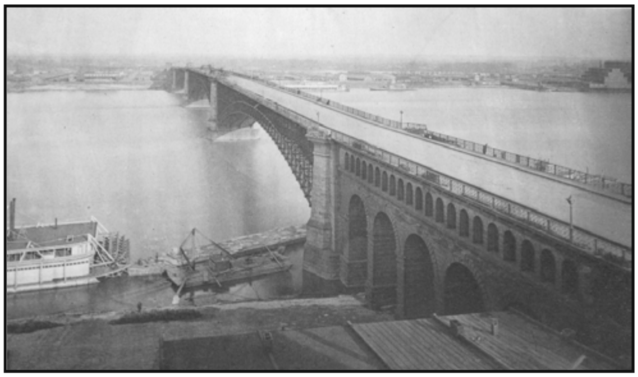
Even today, concerns for safety of compressed air workers remain. These so-called "sandhogs" continue to labor in the pressure environment (30). Although the times have changed, similar difficulties remain. There are multiple schedules for decompression---Milwaukee Tables, Blackpool Tables, Washington State Tables, to name a few---and trials persist to develop the most effective (9,31,32). Both Jaminet and Smith correctly identified the need for a decompression schedule, but both terribly overestimated the proper rate of decompression.

Worker fitness remains important. The pressure environment is a stress-filled place. A worker that is not both medically and physically fit is a danger to himself and, potentially, fellow workers. Care must be taken to exclude unfit workers. Both Jaminet and Smith boldly applied this precept during pre-placement and periodic exams.

And, lastly, treatment has changed---recompression is standard. This idea never crossed Jaminet's mind. Smith, however, correctly deduced its potential. He knew the observations of Bouhy as well as Pol and Watelle; he knew some workers improved when returned to pressure (6). Moreover, Smith himself had seen the same improvement in three workers. Indeed, he delivered a strong recommendation for a medical lock: "…a tube 9 feet long and 3.5 feet in diameter…(it) should be connected by means of a suitable tube with the pipe which conveys the air from the condensers to the caisson." In this way, he could treat the worker with pressure outside the confines of the caisson. He even mentioned Bert's suggestion of oxygen treatment, but failed to pursue it (6). Despite this forward thinking, Smith stopped short of demanding his own recommendation. Had he installed a medical lock, perhaps no deaths would have accompanied the Brooklyn Bridge caissons.

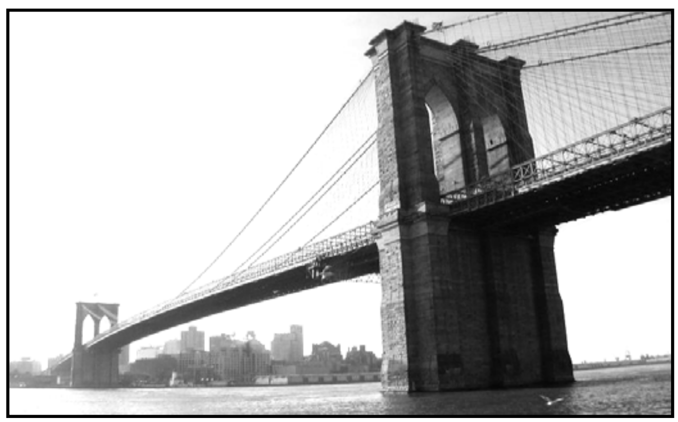
All together, the Eads Bridge produced some 119 severe cases and 14 deaths (16, 29; see Picture 1). The construction was not only a monumental engineering triumph, but also a monumental human tragedy. The Brooklyn Bridge, however, benefited from this tragedy. Washington Roebling knew what had happened in St. Louis. He knew what had happened to himself. He decided to abort deeper penetrations of the East River. As a result, there were 110 cases with only 3 deaths (6; see Picture 2).

Picture 1



Picture 1. The Eads Bridge. Photo of completed bridge taken in 1880. (from Woodward, A History of the St. Louis Bridge; St. Louis: GI Jones and Company; 1881)

Picture 2



Picture 2. The Brooklyn Bridge. Photo by GaryFeuerstein in 2002. (from the Brooklyn ridgeWebsite- www.endex.com/gf/buildings/bbridge/bbridge.html [permission granted with citation] 25 April 2003)

The countermeasures implemented by both Jaminet and Smith proved largely effective. Their attempts to control rapid decompression, a primary prevention target, were woefully inadequate and exceedingly timid. However, they refused to endorse open valve decompression pressing for and obtaining a standard decompression schedule. They successfully negotiated for a resting room and elevator to avoid excessive post-exposure exertion. And, they successfully reduced exposure time by shift shortening. In addition, their screening measures, the secondary prevention target, clearly identified high-risk workers and removed them from the mix. Lastly, their treatment regimes, the tertiary prevention target, were lacking. They were reactive, supportive measures rather than proactive interventions. But, all told, their countermeasures were effective. With Jaminet's actions, the Eads Bridge workers' odds of dying from caisson disease were significantly dropped; with Smith's actions, the Brooklyn Bridge workers' odds of dying from caisson disease were significantly dropped. Clearly, their work is an example of Preventive/Occupational Medicine at its best.

Indeed, the writings of these two physicians had a mighty influence. Their descriptions of decompression sickness are classic and without peer; they remain viable even today. The notion that inappropriate fatigue means decompression sickness and abdominal pain bodes spinal cord involvement dates to Jaminet. The notion of safeguarding the worker by re-engineering the workplace was important to both men; it remains a prime tenet of modern Occupational Medicine. The notion that a worker must be fit for his workplace is just as valid now as then; both Jaminet and Smith emphasized this concept. Finally, Smith's notion of a medical lock might well be termed radical. No one prior to him had argued in such a coherent manner or made such a strong recommendation. Indeed, the construction of the Hudson River Tunnels proved the medical lock's inherent worth (33,34). Undeniably, modern compressed air workers owe much to these early physicians.

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