Forensic Science International 260 (2016) 59–65

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Did the crew of the submarine *H.L. Hunley* suffocate?

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ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form 21 December 2015
Accepted 9 January 2016
Available online 16 January 2016

Keywords:
Hypoxia
Hypercapnia
Hunley
Submarine
Sinking

ABSTRACT

On the evening of February 17th, 1864, the Confederate submarine *H.L. Hunley* attacked the Union ship *USS Housatonic* outside Charleston, South Carolina and became the first submarine in history to successfully sink an enemy ship in combat. One hypothesis for the sinking of the Confederate submarine *H.L. Hunley* is that the crew, in the enclosed vessel, suffered a lack of oxygen and suffocated. This study estimates the effects of hypoxia and hypercapnia on the crew based on submarine gas volume and crew breathing dynamics. The calculations show the crew of the *Hunley* had a minimum of 10 min between the onset of uncomfortable hypercapnia symptoms and danger of loss of consciousness from hypoxia. Based on this result and the location of the crew when discovered, hypoxia and hypercapnia do not explain the sinking of the world's first successful combat submarine.

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1. Introduction

Confederate military commanders hoped that the *Hunley* could sink some of the Union ships blockading Charleston harbor, and thereby end the Union blockade [1,2]. Several military submarines had previously been constructed, such as Alfred Bushnell's *Turtle* during the Revolutionary War, and the Confederate vessels *Pioneer* and *American Diver*, but before the *Hunley* none had been successful in combat [3].

The *Housatonic* was quickly sunk by the *Hunley's* torpedo, and five members of her crew were killed. However, the *Hunley* disappeared immediately after its attack, and even though it was raised from the ocean floor in 2000, the cause of its sinking remains a mystery [4]. It is possible that the vessel was sunk because the crew, in their sealed volume, consumed their limited oxygen supply and succumbed to the effects of hypoxia and/or hypercapnia. This study analyzes limits on the air supply for the crew of the *H.L. Hunley*.

2. Background

2.1. History of the submarine

Before its final disappearance on February 17th, the *Hunley* had sunk twice on training missions, killing a total of 13 crewmen. The *Hunley* was powered by a hand cranking mechanism that was turned by 7 crewmen, with an 8th crewman who served as the commander and navigator [5,6]. In light of the previous sinkings of the *Hunley*, the crew was reportedly forbidden from making the submarine negatively buoyant, even on the night of its attack [7], and was to attack on the surface of the water without fully submerging. This command made the vessel safer to operate and also provides valuable information about its position in the water column because historical drawings are available detailing the attack position [2]. Fig. 1 shows a detailed artistic reconstruction of the *H.L. Hunley* as she would have appeared at the time of her sinking. The figure shows the torpedo in a lowered position. It should be noted that the exact angle of the spar and torpedo relative to the body of the vessel are still uncertain, but that their positions do not impact the results of this study.

2.2. Air exchange

Historical accounts describe a bellows and snorkel tubes designed to circulate air within the body of the submarine, and indeed such a system was discovered upon the vessel's recovery [2,5]. However, little is known about how well this system functioned, or if it functioned at all. Former crewman William Alexander wrote that the bellows never functioned properly, and that fresh air was instead obtained by opening the conning tower hatches every 20 min [2,8]. Other historical accounts were similarly dismissive of the bellows and snorkel system [8]. Indeed, the bellows are not included on any known historical drawings or

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http://dx.doi.org/10.1016/j.forsciint.2016.01.008
0379-0738/Published by Elsevier Ireland Ltd.

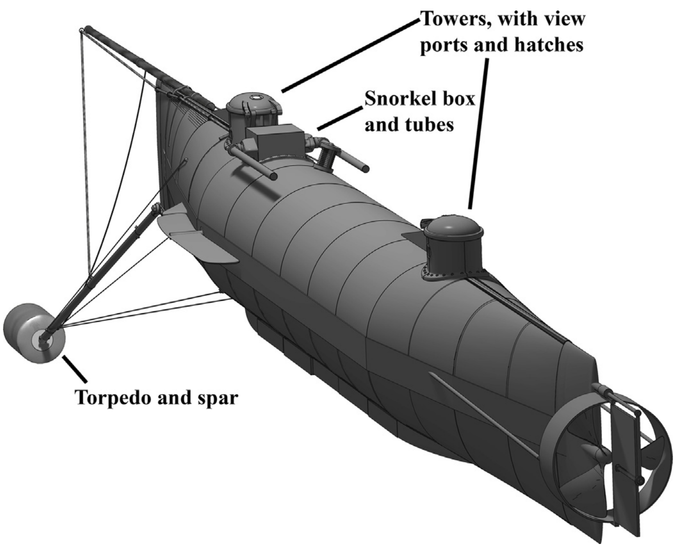

Fig. 1. 3D reconstruction of the *H.L. Hunley* at the time of her sinking. More information and detailed views of the reconstruction can be found at the website http://vernianera.com/Hunley/.

diagrams, perhaps indicating that the draftsmen may have neglected the nonfunctional structure. Aside from the bellows system, the vessel had no means of taking in fresh air other than opening the hatches. This analysis was conducted under the assumption that the historical accounts are accurate, and that the bellows did not function to ventilate the atmosphere of the submarine. This is a conservative assumption since increased ventilation would delay the effects of either hypoxia or hypercapnia.

The crew was acutely aware of the risks of hypoxia in a closed environment, and performed tests to determine the duration of their oxygen supply [2]. The test consisted of holding the vessel submerged, too deep for any possible operation of the bellows, while the crew performed their normal cranking operations with a lighted candle burning.

2.3. Archaeological discoveries

Since its raising in 2000, several archaeological discoveries have been made regarding the *Hunley*. Most importantly, when the sediment was excavated from the inside of the *Hunley*, it was discovered that the remains of all eight crewmembers were still seated at their stations along the crank [9]. The Chairman of the Friends of the Hunley at the time, Warren Lasch, was quoted describing the remains: "The crewmembers' remains being discovered at their stations indicated both a recognition and acceptance of their fate... evidence seems to suggest more and more that the final moments were quick and decisive."[9] Lieutenant George Dixon, who manned the forward command position below the fore conning tower, was described as "right there in his duty station slumped over to one side with his legs up near the bulkhead, exactly where he would have been if he was on duty."[10]. Additionally, geological analysis of the sediment and macrofauna showed that there was a "calm period of little to no deposition" following sinking, indicating that the hull was intact when it sank [11,12].

2.4. Respiration

In clinical research, hand-pedaled arm ergometers are frequently used to measure and control levels of exercise performed by human test subjects; the cranking motion of these ergometers is biomechanically similar to the cranking motion used to propel the *Hunley* [13]. In addition to hypoxia, concurrent hypercapnia from increased carbon dioxide (CO_2) levels for personnel rebreathing gas within an enclosed space is also important. Unlike hypoxia, which may not be evident to sufferers, hypercapnia can cause overt and identifiable symptoms such as sensation of choking, shortness of breath, chest pain, tingling, trembling, headache, nausea, and psychological fear and discomfort [13–15]. The amount of carbon dioxide produced is calculated by multiplying the oxygen consumption by the respiratory exchange ratio (RER), a fractional ratio describing the rate of CO_2 volume produced per unit of O_2 volume consumed. RER at rest is typically around 0.8. RER often increases during exercise, and can exceed 1.0 during heavy exertion.

3. Methods

3.1. Volume estimation

Estimates of oxygen supply within the submarine began with a calculation of the net volume of gas within the submarine. The internal volume was calculated by creating a model of the vessel's hull, then subtracting the volumes of all moderate- to large-sized internal objects. Complex structures (vessel hull, snorkel box and pipes, conning towers, cutwaters, structural ribbing, ballast bulkhead walls, and dive planes) were modeled using the engineering modeling software SolidEdge ST7 (version 107.00.00.104 $\times$ 64, Siemens, 2014) to calculate volumes and masses. Volumes and masses of simpler items were calculated manually. Dimensions were obtained both from values published in released documents (e.g., [3,16,17]) and by measuring items from published photographs that included measurement stadia. A summary of item measurements and volumes are shown in Table 1. While dimensions were measured from photographs rather than the vessel itself, the resulting model closely matches published scans and drawings of the recovered submarine (Fig. 2).

The volumes of the crewmembers were also estimated and subtracted from the internal volume of the vessel. The heights and descriptions of each crewmember were published by the Friends of the Hunley after analysis of the remains by specialists from the Smithsonian Institution [20–30]. The average body mass index of adult male military personnel entering West Point between 1874–1894 was 20.22 ($\pm$1.99 SD); this value was used to compute masses

Table 1
Summary of masses and volumes of all non-trivial objects aboard the *Hunley*. A full listing of items and estimated dimensions is freely available for non-commercial use by request to the authors.

Object	Volume (cm^3)	Mass (kg)
Ballast blocks (internal)	277273	2024
Ballast blocks (keel)	–	1369
Bench, main crew	68447	34
Crank	10963	168
Crew	477810	502
Internal medium-sized objects[a]	152208	–
All medium-sized objects[b]	–	643
Hull assembly (from SolidEdge)[c]	8993312 (internal)	4408
Totals	8006612	8505
Calculated ballast water	394026	404

[a] Includes: bellows, bellows pipe, bench (Dixon's), canteens (8), cask/barrel, compass box, copper plate, crank wall mounts, flywheel, gears, piping, pumps (aft and fore), ribbing, rudder control rods, shelf, and various tools

[b] Includes: bellows pipe, bench (Dixon's), canteens (8), cask/barrel, chain (primary), chain (spare), compass box, copper plate, crank wall mounts, flywheel, gears, piping, propeller, pumps (fore and aft), rudder, rudder control rods, shelf, and various tools.

[c] Includes: central hull, bow and stern tapered hulls, bow and stern cast pieces, snorkel box and pipes, conning towers, cutwater, ribbing through hull/bow/stern (mass only), dive planes.