Epidemiol. Infect. (2013), **141**, 2205–2212. © Cambridge University Press 2013
doi:10.1017/S0950268812003032

Spatiotemporal patterns of pandemic influenza-related deaths in Allied naval forces during 1918

G. D. SHANKS[1,2]*, M. WALLER[3] AND M. SMALLMAN-RAYNOR[4]

[1] *Australian Army Malaria Institute, Enoggera, QLD, Australia*
[2] *University of Queensland, School of Population Health, Brisbane, QLD, Australia*
[3] *University of Queensland, Centre for Military and Veteran's Health, Brisbane, QLD, Australia*
[4] *University of Nottingham, School of Geography, Nottingham, UK*

Received 13 September 2012; Final revision 21 November 2012; Accepted 5 December 2012; first published online 16 January 2013

SUMMARY

This paper draws on the mortality records of the French, US and UK Royal navies to reconstruct the spatiotemporal evolution of the 1918–1919 influenza pandemic in global Allied naval forces. For a total of 7658 deaths attributed to respiratory diseases (French and US navies) and all diseases (UK Royal Navy) at 514 locations worldwide, techniques of spatial point pattern analysis were used to generate weekly maps of global mortality intensity in 1918. The map sequence for the main period of pandemic mortality, mid-August to mid-November 1918, revealed a near-simultaneous development of mutiple foci of high disease intensity in three distant locations (Europe, North America, West Africa). Given the relatively slow speed of naval ships in convoy at this time (<12 knots), our findings suggest that the pandemic influenza virus was circulating on three continents at the observed onset of the main mortality wave.

Key words: Military, mortality, navy, pandemic influenza.

INTRODUCTION

The genesis and initial evolution of the influenza A(H1N1) virus or viruses that caused the 1918–1919 influenza pandemic remain uncertain. This pandemic was associated with an estimated 0·5 billion infections and 20–50 million deaths worldwide and is the world's greatest single infectious disease mortality event for which modern mortality records exist [1]. The return of pandemic influenza A(H1N1) in 2009 with morbidity concentrated in younger age groups and relatively low mortality (estimated case-fatality rate $\ll 1\%$) makes a better understanding of the events leading to the influenza pandemic of 1918–1919 (estimated case-fatality rate 2%) critically important in terms of accessing the risk of future shifts in pathogenicity and lethality [2, 3]. Since no one could have anticipated what occurred in 1918–1919, study of the genesis and evolution of the pandemic depend on historical records, ideally those that were prospectively collected [4].

The influenza pandemic of 1918–1919 was intimately associated with the end of the First World War and the resulting enormous trans-continental population shifts [5]. It has previously been suggested that the battlefields of the First World War with millions of men crammed together in unsanitary conditions may have been where the pandemic viruses of 1918

* Author for correspondence: Professor G. D. Shanks, Australian Army Malaria Institute, Enoggera, QLD 4051, Australia. (Email: dennis.shanks@defence.gov.au)

https://doi.org/10.1017/S0950268812003032 Published online by Cambridge University Press

evolved [6]. Certainly there were ideal conditions for the spread of respiratory viruses on board naval ships and in trenches, but an influenza-like disease was widespread in both military and civilian populations from April to June 1918 and the apparent multi-focal nature of the later wave of lethal influenza limits any attempt to locate a single source of the disease [7, 8]. As early as 30 July 1918, a severe outbreak of respiratory disease in French Army training camps in Lorraine is reported to have resulted in the death of almost 5% of recruits [9]. British warships off Sierra Leone, one of which experienced 7% mortality, were infected with influenza from the HMS *Mantua* which left Portsmouth in southern UK on 1 August 1918 [10]. The US Naval Base Hospital at Brest, France, recorded a sharp increase in respiratory disease mortality from 22 August 1918 [11]. This change from ordinary to lethal respiratory infections occurred from early September 1918 in the American Expeditionary Force (AEF) in France [7]. The same phenomenon was noted in the British Expeditionary Force (BEF) from mid-September to October [12].

Many military organizations of the First World War routinely collected detailed demographic, health and geographical information. This was especially true for all sailor deaths in the French, US and UK Royal navies [13]. Although Allied naval forces were concentrated in the North Atlantic, they included ships deployed globally. By geographically plotting disease deaths in the French, US and UK Royal navies, we sought to elucidate the global progression of the pandemic in this particular branch of the Allied forces.

MATERIALS

Data sources

Information on deaths due to medical illnesses (non-combat, non-accident) in the Allied naval forces of the UK, USA and France was accessed for the final calendar year of the First World War (1918) from three primary sources:

(1) *UK Royal Navy*. A near-complete digitized listing by the Commonwealth War Graves Commission (CWGC) *Debt of Honour Register* (http://www.cwgc.org/; accessed 15 February 2012); available online at http://www.naval-history.net/xDKCas1003-Intro.htm#1914 (accessed 20 November 2012).

Table 1. *Disease-related deaths by UK, USA and French naval forces, 1914–1918*

Year	UK*	USA†‡	France†	Total
1914	184		n.a.	184
1915	1133		n.a.	1133
1916	1181		n.a.	1181
1917	1174	4	n.a.	1178
1918	2640	4381	637	7658
Total	**6312**	**4385**	**637**	**11334**

n.a., Not accessed.
* All diseases.
† Respiratory diseases (pneumonia and influenza) only.
‡ USA did not join the war until 1917.

(2) *US Navy*. The original casualty records of the Bureau of Navigation, Department of the Navy [14] available online at http://www.naval-history.net/WW1NavyUS-Casualties.htm (accessed 20 November 2012).

(3) *French Navy*. The mortality records assembled in the post-war period by Morts pour la France, Mémoire des hommes, Secretarial general pour l'administration, Ministère de la Defense (http://www.memoiredeshommes.sga.defense.gouv.fr/spip.php?rubrique16; accessed 24 August 2012).

For each recorded death, information on the name and rank of the deceased, the ship, medical or other facility at which the death occurred, the date and cause of death and the place of burial was abstracted from sources (1)–(3) to yield a consolidated database of illness-related mortality in the combined naval forces. For the purposes of the present analysis, database entries were limited to: (i) deaths due to respiratory causes (influenza and pneumonia) in the US and French navies; and, owing to the coarser nature of the available information, (ii) deaths due to all diseases as a proxy for respiratory disease (influenza and pneumonia) deaths in the UK Royal Navy. All deaths were geocoded (latitude, longitude) according to the specified (shore-based) place of death; the home port of a ship was used as a surrogate for place of death when a shore-based location was not specified. Summary details of the total number of deaths included within the database for 1918, along with the equivalent information for the respective periods of military engagement of the three navies in earlier years of the conflict, are given in Table 1. Deaths recorded in 1918 form the basis of all the analysis to follow.

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Table 2. *Number of geo-coded locations for disease-related deaths in the combined naval forces, 1918*

World region/country	No. of locations	No. of deaths
Africa	**14**	**148**
Sierra Leone	1	92
Other countries ($n=8$)	13	56
Americas	**218**	**4133**
Brazil	1	55
USA	197	4029
Other countries ($n=13$)	20	49
Europe	**265**	**3328**
England and Wales	77	1813
France	94	896
Germany	6	48
Greece	7	44
Ireland	13	72
Italy	9	44
Malta	1	43
Scotland	35	203
Other countries ($n=12$)	23	165
Other regions*	**17**	**49**
Total	**514**	**7658**

* Including Asia and the Pacific ($n=11$ countries).

Statistical analysis: global mortality patterns

Global patterns of disease mortality in the combined French, US and UK Royal navies in 1918 were examined using techniques of spatial point pattern analysis [15, 16]. For a 53-week period, bracketed by the weekly intervals that encompassed the opening (week ending Sunday 6 January 1918) and closing (week ending Sunday 5 January 1919) days of 1918, the dataset consisted of 7658 deaths at 514 locations in 55 countries (Table 2). The subset of deaths in a given week was then treated as a spatial point pattern, with the first order properties of a spatial point process used to describe how mortality intensity (the mean number of deaths per unit area) varied through space. In general, following Gatrell and colleagues [16], the intensity $\lambda(s)$ of a spatial point process is defined as the mathematical limit

$$\lambda(s) = \lim_{ds \to \mathbf{0}} \left\{ \frac{E(Y(\boldsymbol{ds}))}{ds} \right\}, \quad (1)$$

where $\boldsymbol{ds}$ is a defined region around the point s, $E(\ )$ is the expectation operator, ds is the area of the region and $Y(\boldsymbol{ds})$ refers to the number of events in the region. For the purposes of the present analysis, weekly mortality intensities were computed in S+ SpatialStats version 1.5, release 1 (MathSoft Inc., USA) with a quartic kernel estimator [17]. Estimation was undertaken at the global level using (i) a temporally variable spatial unit for intensity that was scaled to the number of deaths in a given week (mean 6·71 million km²; range 0·09–9·90 million km²) and (ii) a fixed bandwidth of 5750 km. Here, the choice of bandwidth was based on an exploratory examination of intensity surfaces using different degrees of smoothing and reflected the desire to capture regional trends (rather than national or subnational variations) in the distribution of mortality.

RESULTS

Figure 1 plots the combined weekly time-series of mortality due to diseases in the French, US and UK Royal navies for January–December 1918. Following Patterson & Pyle [18], time periods of particular interest for the evolution of pandemic influenza include:

(i) March–June 1918, a period of low influenza mortality/high influenza morbidity that is commonly designated as the 'first wave' (wave 1) of the pandemic.
(ii) September–December 1918, the 'second wave' (wave 2) of the pandemic, when most deaths occurred.

Summary details of naval deaths in these two time periods, along with the corresponding information for the 'non-pandemic' intervals of January–February and July–August 1918, are given in Table 3.

The mortality signal for the period March–June 1918 is low and approximately constant (Fig. 1), with little or no change in the average daily count of deaths compared to the months immediately preceding wave 1 (Table 3). Despite the fact that the French, US and UK Royal navies were using the same French seaports to support the war effort, their pandemic mortality peaks indicate sequential epidemics starting in the French Navy in August/September, progressing to the US Navy in September/October and then the British Navy in October/November (Fig. 2). Although not shown, this same sequence is also evident in the crude mortality series for the three navies and suggests that, despite the geographical proximity of sailors of different nationalities in the same ports, infection was moving sequentially through the French Navy, followed by the US Navy and finally in the UK Royal Navy and ending at about the same time that the respective land forces were also experiencing pneumonia/influenza mortality [4, 7, 9].

https://doi.org/10.1017/S0950268812003032 Published online by Cambridge University Press

Table 3. *Disease-related deaths in naval forces by time interval, 1918*

	Naval force*			
Time period	UK†	USA‡	France‡	Grand total
1 January–28 February	184 (3·12)	254 (4·31)	2 (0·03)	440 (7·46)
1 March–30 June (wave 1)	**452 (3·70)**	**396 (3·25)**	**0 (0·00)**	**848 (6·95)**
1 July–31 August	362 (5·84)	57 (0·92)	71 (1·15)	490 (7·90)
1 September–31 December (wave 2)	**1642 (13·46)**	**3674 (30·11)**	**564 (4·62)**	**5880 (48·20)**
Total	2640 (7·23)	4381 (12·00)	637 (1·74)	7658 (20·98)

* Number of deaths per day in parentheses.
† All diseases.
‡ Respiratory diseases (pneumonia and influenza) only.

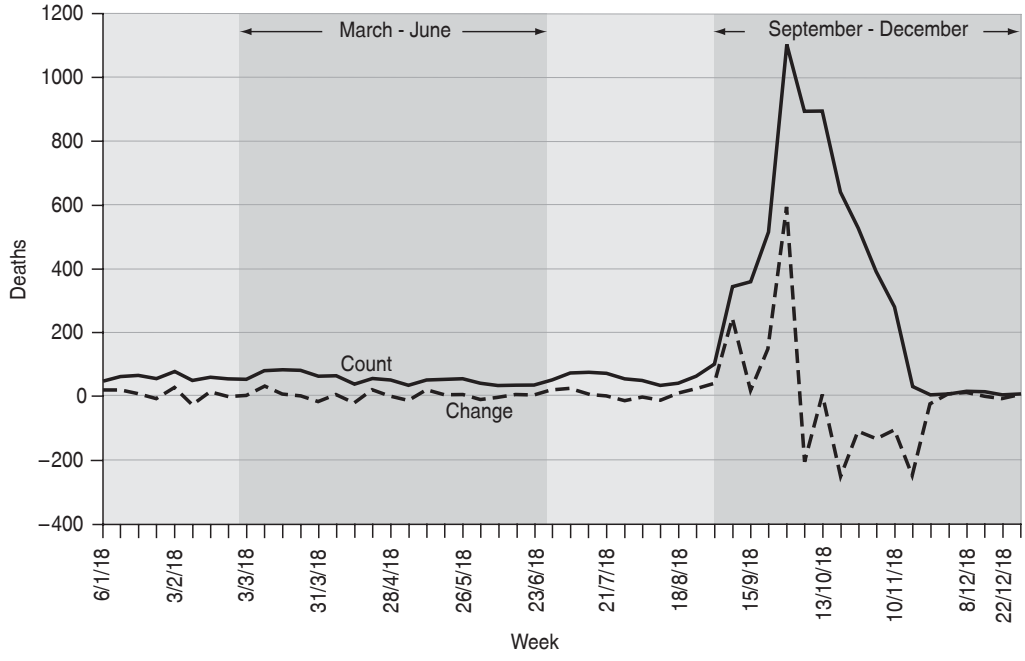

Fig. 1. Weekly series of deaths due to disease in the combined French, US and UK Royal navies, January–December 1918. The count of deaths d_t in a given week t is plotted as the full line traces; the weekly change in deaths ($d_t - d_{t-1}$) is plotted as the broken line traces. Intervals corresponding to the recognized periods of heightened influenza activity in 1918 (March–June and September–December) are indicated.

To depict the global pattern of deaths associated with the mortality waves in Figure 2, the map sequence in Figure 3 has been generated from the spatial point pattern analysis and plots mortality intensity in the three navies at weekly intervals from mid-August to mid-November 1918. It should be noted that the mapped intensities have been log-transformed to facilitate the visualization of focal areas of mortality in the range of tens (e.g. West Africa) to thousands (e.g. Europe and North America) of deaths (Table 2).

Beginning with low levels of mortality in mid-August, Figure 3 shows the rapid and near-simultaneous development of mutiple foci of high disease intensity on three continents (northern Europe, northeastern United States, West Africa) in late August and early September. Mortality peaked in the week ending 29 September (Fig. 1) and, from thereon, Figure 3 depicts a geographical extension of mortality foci to include locations in the Southern Hemisphere (Brazil, Peru, South Africa, Tanzania), South and Southeast Asia (India and the Philippines)

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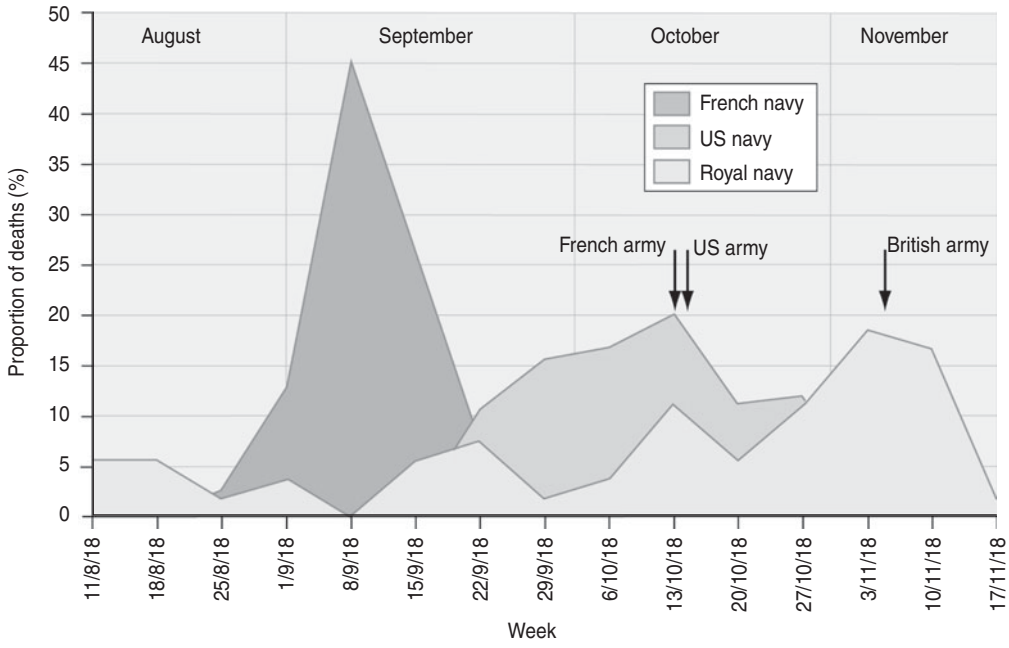

Fig. 2. [*colour online*]. Proportional disease mortality in the French, US and UK Royal navies during the autumn influenza wave, August–November 1918. For each organization, the graph plots the number of deaths in a given week as a percentage proportion of the total mortality count for that organization in the period August–November 1918. The chart depicts the sequential progression of mortality peaks in August/September (French Navy), September/October (US Navy) and October/November (UK Royal Navy). Peak influenza-related mortality is also indicated by arrows for the French, USA and UK armies as determined from official histories [19, 30].

and, towards the end of the pandemic wave, the western Pacific (Guam). A rapid diminution of recorded mortality in all locations accompanied the Armistice in mid-November.

DISCUSSION

The British Official Medical History of the Great War states that 'Ordinary influenza was never absent from the various army commands' [19]. Despite the constant presence of influenza-like illness, only twice during the First World War did influenza severely impact on British military operations: April–July 1918 when very large numbers of sailors and soldiers were incapacitated by a high morbidity/low mortality illness and September–December 1918 when fewer became ill, but thousands died [12]. During the winter of 1916–1917, outbreaks of clinically distinct, lethal respiratory disease in British sailors and soldiers in both the UK and France occurred; it has previously been suggested that these 'purulent bronchitis' epidemics were in reality the beginning of the 1918 pandemic [6, 17, 20]. Neither investigators at the time nor more recent efforts, including our own, have been able to trace a direct chain of lethal disease from early 1917 to late 1918 [21]. Given the known seasonality of influenza, this is not surprising and therefore neither confirms nor invalidates the hypothesis that the influenza virus which caused the 1918–1919 pandemic was circulating in Europe in the years prior to the main lethal wave in late 1918. Descriptions of further outbreaks of lethal respiratory disease during the winter of 1917–1918 occurred in New Zealand soldiers in training bases in the UK and US soldiers just arriving in France [22, 23]. Whether these or other reports represent a new influenza virus trying to adapt to its host cannot be determined at this distance in time only from written records but the data are consistent with such a hypothesis [8, 24].

For the purposes of the present analysis, we have drawn on standard sources of mortality in the French, US and UK Royal Navies in 1918. Although it is impossible to determine if all the deaths included in these sources were appropriately recorded, we note that they represent the most complete set of records for sailors of the three Allied navies who died during the First World War. While the sources for the French and US navies have allowed us to differentiate deaths due to respiratory disease (influenza/pneumonia) from other causes, similarly detailed medical records are not available for the UK Royal Navy and we have used all disease deaths as a proxy measure of

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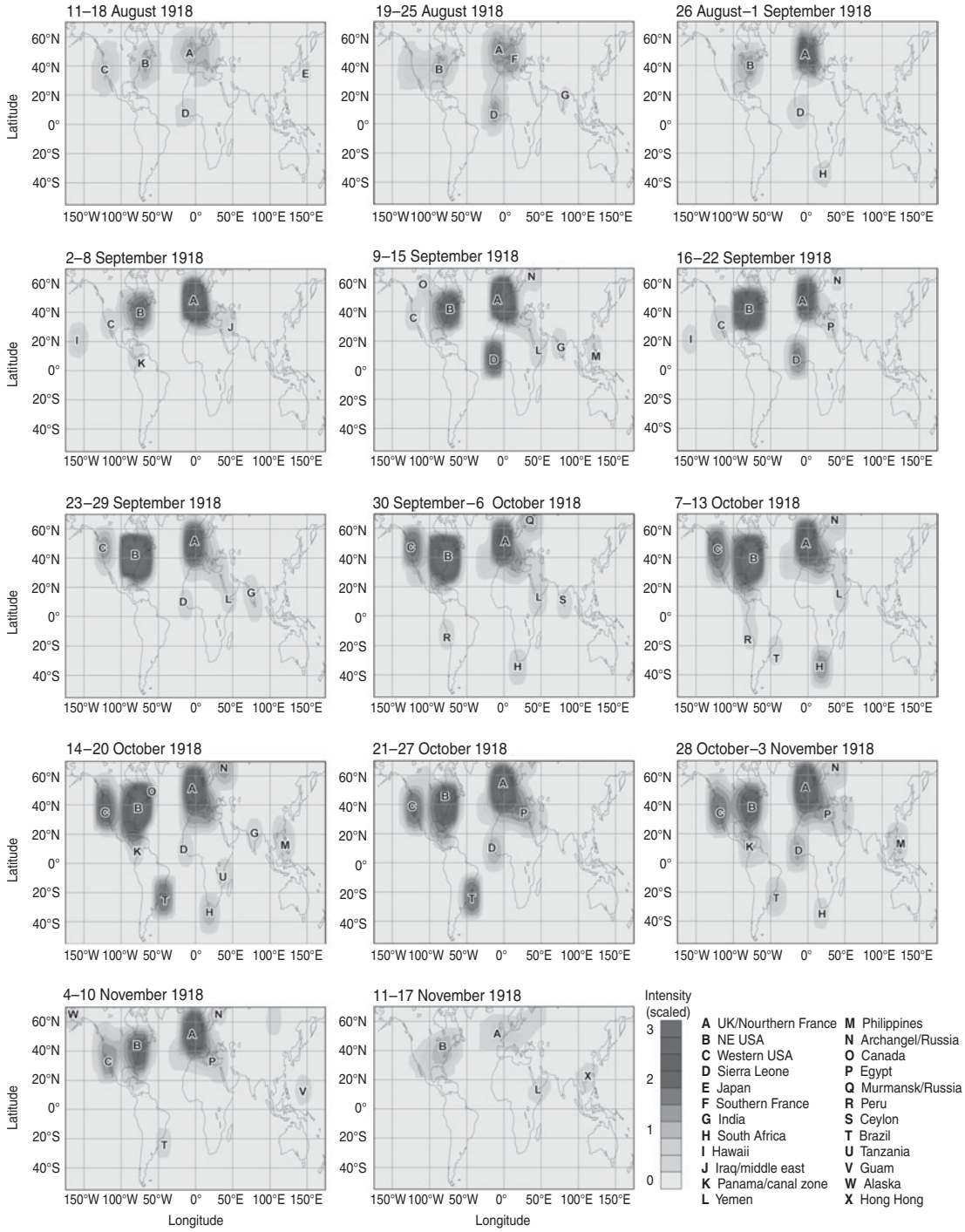

Fig. 3. [*colour online*]. Weekly intensity of disease-associated mortality in the combined French, US and UK Royal navies, August–November 1918. Areas of relatively high mortality intensity are represented by the relatively darker shaded categories.

respiratory disease mortality in this force. Although our use of a proxy measure is sub-optimal, we note that there is a strong correspondence in time between the pandemic mortality signals for the three navies. On this basis, and informed by published evidence on the role of influenza/pneumonia as a cause of death on UK Royal Navy vessels [10], we infer that our proxy measure provides an adequate means of monitoring the progression of the lethal 1918 pandemic wave.

It is important to emphasize that the spatio-temporal patterns described in this paper relate to a

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specific set of naval organizations that, although globally distributed, were largely concentrated in the North Atlantic. While the results of our analysis should be interpreted in this context, we note that the map sequence in Figure 3 does provide far greater spatial and temporal precision to the global spread of the August–November 1918 influenza wave than has been achieved in previously published reconstructions of the pandemic [18]. Another limitation is our inability to calculate population rates. Although both the UK and USA navies can be estimated at 500000 men in late 1918, the constant movement inherent in naval forces does not allow us to accurately estimate populations at particular locations.

Despite detailed descriptions of the first wave of influenza-like illness in early to mid-1918 globally, no pronounced mortality signal in the combined navies was detected (Fig. 1). This is consistent with the mortality estimates in the French Army (approximate strength: 4 million men) where fewer than 100 men were thought to have died in the first wave, compared to 28000 in the second wave in late 1918 [9]. Australian Army data indicate that mortality due to pneumonia or influenza in France was largely restricted to newly recruited soldiers and this was also true in the French Navy [4]. This marked difference in lethality between the two epidemic waves has been previously described but not explained. Hypotheses include the rapid evolution of pathogenicity in a single virus or replacement by an entirely different H1N1 virus [25, 26].

The French, US and UK Royal navies shared the same Atlantic seaports during a massive movement of soldiers due to the war (2 million in the US Army alone). Seaports were epidemiological centres of influenza spread in 1918 similar to airports during the 2009 pandemic. Despite using the same French ports, the naval and army epidemics were asynchronous reflecting the differences in numbers and location of the respective national military forces. The mortality wave in the three Allied navies using French ports appears to have moved sequentially through the navies (Fig. 2) as might be expected from an infectious respiratory pathogen. The near-simultaneous increase in influenza mortality in naval units on three continents is inconsistent with the recent spread of a newly evolved, highly pathogenic influenza virus especially considering that ships in convoy usually moved at <12 knots (Fig. 3). If the extraordinary lethality of influenza in late 1918 was due to a single influenza virus, as seems likely from recent genomic reconstruction from pathological specimens, then the virus must have already been globally distributed prior to mid-1918. This view has recently been confirmed by the examination of preserved autopsy specimens from soldiers dying in US Army training camps where viral genomic material similar to that found late in 1918 was identified as early as May along with no distinguishable qualitative differences in pathology between pre-pandemic (May–August) and subsequent deaths in 1918 [27]. Efforts to reconstruct the genomic development of influenza viruses also suggest that the virus causing the 1918 pandemic had been evolving in people for several years prior to the pandemic outbreak [28].

The 1918 influenza pandemic has been described as 'a puzzle with missing pieces' [29]. The puzzling issues include the uniquely increased lethality in young adults which appeared almost simultaneously across the globe. Our observations have admittedly been restricted to naval populations but sailors were of the ages most at risk of death and were the global military group who maintained detailed prospectively collected morbidity and mortality data. Examination of mortality information specific to named individuals first in the Australian Army and now in Allied naval forces indicates that simplistic explanations of what happened in 1918 do not fit the data. The 'missing puzzle pieces' include multiple viral isolates from globally distributed populations. Since the 1918 pandemic predated virology and despite heroic efforts with the few surviving pathological samples, it is unlikely we will ever have the primary data to fully answer what really happened during the 1918 influenza pandemic [29]. However, great epidemiological records were collected by our scientific predecessors and they continue to be uncovered in archives. Modern hypotheses can be tested against these old data to help resolve the 1918 influenza pandemic puzzle. Given the surprises generated by a similar H1N1 virus during the influenza pandemic of 2009, such puzzles are well worth solving if we are ever to understand the unique lethality of the 1918 influenza pandemic.

ACKNOWLEDGEMENTS

We thank Alison MacKenzie at the University of Queensland, Centre for Military and Veterans Health for assistance with the data, Professor Peter Dennis of the University of New South Wales at the Australian Defence Force Academy, Canberra, Australia for historical insights, Ms. Odette Hopwood the librarian at Australian Defence Force Library Services,

https://doi.org/10.1017/S0950268812003032 Published online by Cambridge University Press

Gallipoli Barracks and other librarians for help in locating data and Dr John F. Brundage for his critical reading of an earlier version of the manuscript.

This work was supported by the Global Emerging Infections Surveillance and Response System (GEIS) (http://afhsc.mil/geis) at the Armed Forces Medical Surveillance Center of the U. S. Department of Defence.

The opinions expressed are those of the authors and do not necessarily reflect those of the Australian Defence Force or the US Department of Defense.

DECLARATION OF INTEREST

None.

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