The Potential Effects of Burn Pit Exposure on the Respiratory Tract: A Systematic Review

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ABSTRACT

Introduction:

Burn pits (BPs) have been widely used by the U.S. military for waste disposal while in conflicts abroad. Significant adverse health effects are thought to be linked to BPs, but limited data exist examining the impact on the respiratory tract. The purpose of this systematic review is to characterize these effects on both the upper respiratory tract (URT) and lower respiratory tract (LRT).

Materials and Methods:

A systematic review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines on articles published from January 1, 2001, through November 2020. PubMed, EMBASE, and Ovid MEDLINE databases were queried for studies examining the effect of BPs on the URT and LRT of service members.

Results:

A total of 288 articles were identified, with nine meeting inclusion criteria. Eight of the nine articles assessed the LRT, one examined the URT alone, and two examined both the URT and LRT. Outcome measures were heterogeneous across all studies, precluding meta-analysis. Patient-reported LRT diagnoses appeared to increase as exposure to BPs increased. There are very limited data assessing the impact of BP exposure on the URT. No association between BP exposure and objective measures of LRT or URT disease was identified.

Conclusion:

Service members deployed to combat zones seem to report a significant increase in respiratory diseases following exposure to BPs, although definitive conclusions are limited by multiple airborne exposures and varied reporting methods. Self-reported LRT diagnoses appear to be more prevalent. There is a paucity of data on the effects of BPs on the URT. Objective measures of disease do not appear to correlate with patient reports. Prospective, long-term, and outcome-based studies are necessary to examine the effects of BPs, and other airborne hazards related to deployment, on the URT and LRT of service members.

BACKGROUND

Waste disposal in open-air burn pits (BPs) was a common practice in Iraq and Afghanistan during Operation Enduring Freedom and Iraqi Freedom (OIF) from 2001 to 2009.[1] Reports of adverse health effects among returning service members (SMs) who were exposed to these BPs began gaining national attention in the media as well as in academic and military circles within the first few years of the war.[2–5] Of the many hazardous environmental exposures faced by SMs while deployed, BPs stand out due to their ubiquitous presence and close proximity to the warfighter. Environmental sampling in the vicinity of BPs demonstrated the release of multiple chemical compounds as well as coarse respirable particulate matter 10 μm in diameter or less (PM_{10}) and fine particulate matter 2.5 μm in diameter or less ($PM_{2.5}$). These types of particulate matter have been shown to induce inflammation and tissue injury in cell and animal models.[6–8]

Among putative targets of injury from environmental exposures, the respiratory tract (RT) stands out as one of the most likely organ systems to suffer harmful effects. Many of the health problems associated with particle pollution involve the RT, to include irritation of the airway, coughing, difficulty breathing, asthma, sinusitis, or bronchitis.[9,10] Both the upper

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respiratory tract (URT), which includes the nasal cavities, nasopharynx, oral cavity, oropharynx, and larynx superior to the vocal folds, and the lower respiratory tract (LRT), which includes everything below the vocal folds, are at risk from inhalational exposures. As more and more SMs return from deployment with symptoms and diseases involving the RT, concern over the possible role of BP exposure in particular has grown.[11–14] Despite this, limited data exist examining the effect of BP exposure on the RT. The purpose of this systematic review is to characterize the effects of BP exposure on both the URT and LRT.

METHODS

A comprehensive, qualitative review of the English language literature was performed from the PubMed, EMBASE, and OVID MEDLINE databases. The search was conducted in November 2020 using the following terms: "burn pits" OR "burn pit" OR "incinerator" AND "respiratory tract" OR "sinuses" OR "sinus" OR "lung" OR "upper respiratory tract" OR "lower respiratory tract". Inclusion criteria were defined using the Population, Intervention, Control, Outcome, and Study Design approach (Table I).[15] Studies included in the review were those with adult active duty service members (ADSMs), aged 18 years or older, on deployment to the Middle East or Southwest Asia with exposure to BPs, and data relating to URT and/or LRT disease. Case–control, retrospective cohort studies, and prospective cohort studies were included for the initial review. A systematic search of the literature was performed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses literature selection process.[16] Included articles were restricted to items published from 2001 to November 1, 2020.

Two reviewers (J.M. and D.A.) independently examined all articles in a standardized manner to determine study eligibility and then compared highlighted articles. All duplicate records were removed. The abstract of every citation was screened for relevance to RT disease with BP exposure amongst ADSM. Case reports, presentations, and irrelevant articles were discarded. Full-text articles were then assessed for eligibility. Reviews and studies with no data on either BP exposure or RT diseases were excluded. The remaining articles were included for qualitative synthesis.

Data collected from each study included authors, year of publication, study design, patient demographics, patient population, number of patients, reported exposures, and subjective and objective outcomes measures of URT and LRT disease, including quality of life questionnaires, spirometry, pulmonary function tests, bronchoscopy, lavage, CT, and ICD-9 diagnoses. The risk of bias was assessed at the study level by examining study design, source of data collection, and the author's stated purpose for the study. The level of evidence was determined according to the guidelines defined by the Center for Evidence-Based Medicine to provide an estimate of the strength of the study (Table II).[17]

TABLE I. PICOS Criteria

Criteria	Inclusion criteria	Exclusion criteria
Population	Adult (18 years or older) U.S. or foreign military service members deployed to Iraq or Afghanistan	
Intervention	Service members with burn pit exposure while deployed	No data demonstrating burn pit exposure while deployed
Control	Service members without burn pit exposure	
Outcome	Diseases or symptoms of upper or lower respiratory tract in patients with burn pit exposure while deployed	No respiratory health data
Study design	Retrospective cohort, prospective cohort, cross-sectional	Case report, case series, reviews

Abbreviation: PICOS, Population, Intervention, Control, Outcome, Study Design.

A meta-analysis could not be performed because of the heterogeneity in reporting of respiratory disease and outcomes measures.

RESULTS

The initial database query identified a total of 288 articles (Fig. 1). After the duplicates were removed, the abstracts of the remaining 159 citations were screened for articles related to BP exposure amongst ADSM with RT disease. The remaining 48 articles from this initial screen underwent a full-text assessment for eligibility.

A total of nine articles met final inclusion criteria for systematic review (Table III). Four studies were prospective cohort designs, four were retrospective cohort studies, and one was a cross-sectional survey. Eight of the nine articles examined the LRT, with five examining the LRT alone. One study analyzed ICD-9 diagnoses from military treatment facilities within 48 months after deployment, while two studies examined database registries including the Millennium Cohort Study (MCS) and the Veterans Affairs (VA) Airborne Hazards and Open Burn Pit Registry (AH&OBPR). Three studies enrolled patients who presented to pulmonary clinics or were referred to a pulmonologist with LRT symptoms post-deployment. One study was a survey of veterans who had deployed, another examined SMs with BP exposure matched to never-deployed SMs, and the last looked at the prevalence of exercise-induced bronchoconstriction (EIB) following BP exposure. In total, 209,423 patients were included in this systematic review, with 25,081 of these patients having known or reported BP exposure.

TABLE II. Quality of Evidence

Study	Study design	Stated purpose of study	Source of patient data	Level of evidence
Morris et al., 2012[18]	Prospective cohort	Evaluate new respiratory symptoms post-deployment to identify potential etiologies	Objective (CT, PFTs, bronchoscopy) and subjective (surveys) data obtained during evaluation	3b
Smith et al., 2012[19]	Retrospective cohort	Investigate respiratory illnesses and open BP exposure among Millennium Cohort Study (MCS) participants who were deployed to Iraq or Afghanistan	Defense Manpower Data Center (DMDC), MCS	3b
Abraham et al., 2014[20]	Retrospective cohort	Investigate association between deployment to Middle East, open BP exposure, and medical encounters for respiratory causes	Defense Medical Surveillance System (DMSS), DMDC	3b
Liu et al., 2016[21]	Retrospective cohort	Determine the association between BP exposure and incidence of respiratory and cardiovascular conditions	Airborne Hazards & Open Burn Pit Registry (AH&OBPR), DMDC	3b
Rohrbeck et al., 2016[22]	Retrospective cohort	Assess long-term health impact of BP exposure among U.S. service members	DMSS, DMDC	3b
Klein-Adams et al., 2020[23]	Prospective cohort	Determine rate of EIB among recently deployed service members with and without BP exposure	Objective (PFTs, exercise testing) and subjective (surveys, questionnaires) data obtained during evaluation	3b
Morris et al., 2020[24]	Prospective cohort	Perform evaluation on those with chronic RT symptoms post-deployment to identify possible etiologies	Objective (CT, PFTs, laryngoscopy, and labs) and subjective (surveys) data obtained during evaluation	3b
Powell et al., 2020[25]	Prospective cohort	Determine if self-reported BP exposure is associated with OSA	Patient survey, polysomnogram, CT, PFTs, and labs	3b
Poisson et al., 2020[26]	Cross-sectional survey	Survey veterans to gather information that may improve care	Patient survey	5

Abbreviations: AH&OBPR, Airborne Hazards & Open Burn Pit Registry; BP, burn pit; DMDC, Defense Manpower Data Center; DMSS, Defense Medical Surveillance System; EIB, Exercise-Induced Bronchoconstriction; MCS, Millennium Cohort Study; OSA, obstructive sleep apnea; PFT, pulmonary function tests; RT, respiratory tract.

Three prospective cohort studies examined LRT diseases associated with BP exposure in SMs following deployment.[18,23,24] Morris examined patients with LRT symptoms and attempted to identify an etiology in the STAMPEDE I and STAMPEDE III trials, while Klein-Adams assessed the rate of EIB among non-treatment-seeking veterans. A total of 392 patients between the three studies responded to surveys regarding environmental exposures while deployed. STAMPEDE III reported the mean frequency and severity of exposure. Results were similar for both sand/dust exposure and BP exposure, with an average of regular exposure of mild-to-moderate severity among the 326 patients who completed surveys. Of the 74 patients who completed exposure surveys in the other two studies, 60 (81%) reported significant BP exposure while 63 (85%) reported significant exposure to dust/sand. Objective diagnostic testing among the three studies was comprehensive and included laboratory examination, complete pulmonary function tests (PFTs), exercise challenge testing, electrocardiogram, chest X-ray, chest CT, flexible laryngoscopy, bronchoscopy, and bronchoalveolar lavage. In total between the two STAMPEDE studies, the largest cohort of patients were those with undiagnosed exertional dyspnea despite testing ($n = 143$, 33%). Ninety-five (22%) patients were diagnosed with asthma, 67 (16%) with airway hyperreactivity, and 41 (10%) with airway disorders, with 25 (6%) diagnosed with vocal cord dysfunction. The remainder of patients had other uncommon pulmonary diagnoses.

Powell performed a subgroup analysis of the STAMPEDE III study specifically looking at the effect of BP exposure on sleep-disordered breathing.[25] A total of 100 patients were included and were divided into BP-exposed and BP non-exposed cohorts. Among the two cohorts, there was no significant difference in the prevalence of obstructive sleep apnea (OSA) (69% vs. 71%, $P = .83$) and the severity of OSA was higher in the BP non-exposed group.

Four retrospective articles utilized demographic data drawn from the Defense Manpower Data Center, Defense Medical Surveillance System, and/or Armed Forces Health Surveillance Center to identify cohorts with exposure to BPs from 2003 to 2008.[19–22] All four of these studies examined exposure to multiple BP locations, with all including data from BP exposure at Joint Base Balad (JBB). Abraham and Liu also examined BP exposure at Camp Taji, while Smith included patients with BP exposure at Camp Taji and Camp Speicher in addition to JBB. Lastly, Rohrbeck examined cohorts with exposure at Bagram Airfield as well as JBB.

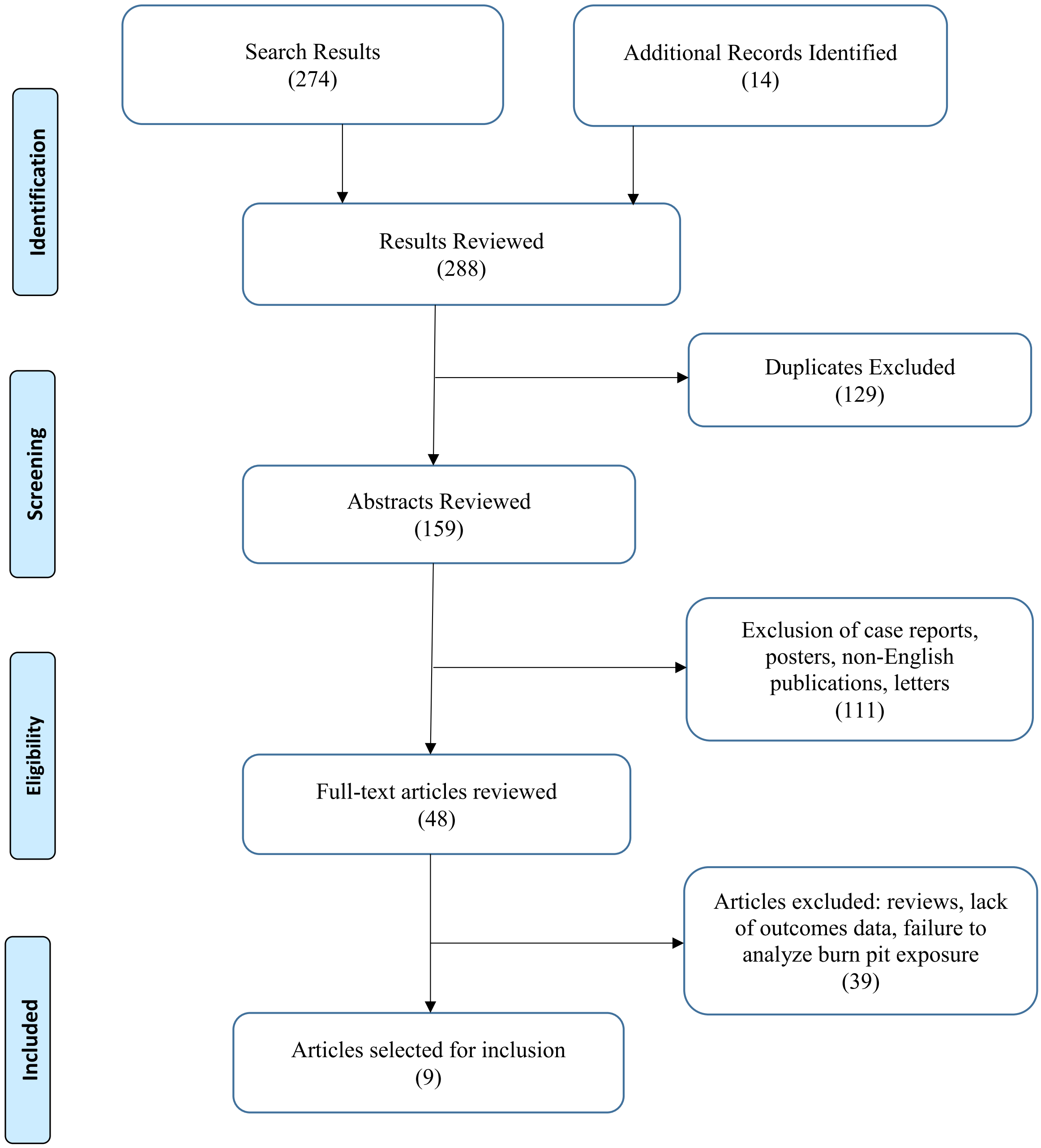

FIGURE 1. PRISMA flow diagram for the literature selection process. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

Of these four retrospective cohort studies, two studies, Abraham and Rohrbeck, looked exclusively at ICD-9 codes in the military health system as objective surrogates for LRT disease.[20,22] Included in these studies were 21,293 SMs with BP exposure and 165,270 SMs in control cohorts (52,979 deployed with no BP exposure and 112,291 never deployed). Abraham found that deployment in support of OIF was associated with a statistically significant increase in the rate of respiratory symptoms and asthma relative to the U.S.-stationed control cohort. In contrast, when comparing the two cohorts that deployed to OIF, the BP exposed group did not have an increased rate of ICD-9 codes related to LRT symptoms, asthma or COPD relative to the group with no BP exposure. Rohrbeck likewise examined ICD-9 codes and found no increased risk for LRT symptoms or LRT diseases and no ICD-9 codes for the URT assigned to ADSM medical records.

Liu examined both subjective and objective measures for LRT health outcomes associated with BP exposure among 4,343 VA patients who completed the AH&OBPR questionnaire.[21] When analyzing ICD-9 codes from the VA medical system and dividing the cohort into quartiles based on

TABLE III. Studies Analyzing Effects of Burn Pit Exposure on URT and LRT

First Author and Year	Study design	Site examined	Study population	Findings	Limitations
Morris, 2012[18]	Prospective cohort	LRT	STAMPEDE I: 50 SMs with no prior diagnosis and new symptoms within 6 months post-deployment	– 78% of cohort (n =39) with BP exposure with 41% reporting adverse health effects – 42% (n =21) remained undiagnosed and 36% (n =18) had airway hyperreactivity	– No correlation of reported BP exposure with objective measures of disease (tests) – Small sample size
Smith, 2012[19]	Retrospective cohort	LRT	Millennium cohort study: – 22,297 SMs deployed to Iraq or Afghanistan and completed survey questionnaire divided into BP-exposed and non-exposed cohorts – 3,585 deployed to BP locations	– No increased risk for asthma (AOR 0.94, 95% CI 0.70–1.27), emphysema/chronic bronchitis (AOR 0.91, 95% CI 0.67–1.24), or LRT symptoms (AOR 1.03, 95% CI 0.94–1.13) between the two cohorts – Increased risk for LRT symptoms in subgroup with BP exposure at JBB (OR 1.24, CI 1.01–1.52)	– Survey utilization – Patient self-reported diagnoses – Limited follow-up time
Abraham, 2014[20]	Retrospective cohort	LRT	SMs deployed for OIF (n = 22.861) compared to two reference cohorts (n = 157,053) in USA and Korea. OIF group with BP exposure (n = 18,430) and no BP exposure (n =6,337) ICD-9 codes from military treatment facilities examined 48 months post-deployment for all cohorts	– Increased incidence of respiratory symptoms (IRR =1.25, 95% CI: 1.20–1.30) and asthma (IRR =1.54, 95% CI: 1.33–1.78) in both OIF cohorts relative to USA cohort – Higher incidence of asthma in BP-exposed cohort relative to USA cohort (IRR =1.59, 95% CI 1.35–1.87) – No difference in LRT symptoms (IRR 0.95, 95% CI 0.88–1.03), asthma (IRR 0.93, 95% CI 0.69–1.25), or COPD (95% CI 0.90, 95% CI 0.65–1.23) between BP-exposed and non-exposed OIF cohorts	– Estimated BP exposure solely on basis of deployment to a base with known BP – Limited follow-up time (4 years) – Multiple confounders not addressed (smoking status, occupation, industrial exposures)
Liu, 2016[21]	Retrospective cohort	LRT, CV	VA AH&OBPR: Deployed with BP exposure (n =2,663) compared to deployed with no known BP exposure (n =1,680) Used questionnaire results and ICD-9 codes from VA health system	– Dose–response relationship between increased time around BPs and increased self-reported COPD/chronic bronchitis (P-trend = .01 and .0005, respectively) and HTN (P = .003) – No association between BP exposure and ICD-9 codes for asthma (OR range 0.75–1.22, P = .17) or COPD/chronic bronchitis (OR range 0.73–1.45, P = .38)	– VA medical records only available for a subset of the cohort – Both exposure and outcome partially self-reported – Objective medical data drawn from only the VA health system

(continued)

TABLE III. (Continued)

First Author and Year	Study design	Site examined	Study population	Findings	Limitations
Rohrbeck, 2016[22]	Retrospective cohort	LRT, URT, multiple others	200 SMs with known BP exposure matched to 200 never-deployed SMs. Analyzed ICD-9 codes from medical encounters for both cohorts	– No increased risk for LRT symptoms (RR = 0.583, 95% CI 0.302–1.128) or LRT diseases (RR = 0.976, 95% CI 0.631–1.508) between BP-exposed and non-deployed control cohort – No ICD-9 code for URT (oral cavity cancer) recorded in any patients	– Low power – Did not account for smoking status – Cohort with BP exposure involved two groups that deployed 5 years apart to different countries
Klein-Adams, 2020[23]	Prospective cohort	LRT	24 asymptomatic veterans completed questionnaire and underwent formal testing for EIB	– 87% ($n = 21$) with significant BP exposure while deployed – 17% ($n = 4$) positive for EIB, similar prevalence to population – 42% ($n = 10$) with probable EIB	– Small sample size – No correlation between BP exposure and test results – No objective assessment of BP exposure
Morris, 2020[24]	Prospective cohort	LRT, URT	STAMPEDE III: 380 SMs who had deployed to Iraq or Afghanistan with chronic LRT symptoms. Completed survey based on VA AH&OBPR and underwent diagnostic battery	– 86% completed exposure survey ($n = 326$) – Respondents indicated a regular exposure to burn pits and sand/dust with a mild-to-moderate intensity over their deployments – 32.1% ($n = 122$) remained undiagnosed, while 23% ($n = 87$) had asthma and 15% ($n = 57$) had airway hyperreactivity – 6.6% of cohort ($n = 25$) found to have vocal cord dysfunction	– Exposure data listed as means and not recorded by number of patientsx – Exposure to BPs not correlated with any particular disease outcome – No objective assessment of BP exposure
Powell, 2020[25]	Prospective cohort	URT	Drew from STAMPEDE III (above): 100 SMs who completed survey, spirometry, met criteria for and underwent PSG. Divided into BP-exposed ($n = 45$) and non-exposed ($n = 55$)	– Between BP-exposed and non-exposed cohorts, no significant difference in prevalence of OSA (69% vs 71%, $P = .83$) – Mean AHI was higher in nonexposed cohort (19.7 vs. 12.3, $P = 0.04$) – Subgroup analyses of BP workers and those with >12 h/day of BP exposure showed no difference in prevalence or severity of OSA	– Drew patients from a preselected cohort that all had chronic LRT symptoms – Did not account for many confounders specific to OSA – No objective assessment of BP exposure
Poisson, 2020[26]	Cross-sectional survey	LRT	Informal recruitment of 109 veterans who served in Iraq from 2003 to 2011 via social media and internet. Questionnaire modeled off of the VA AH&OBPR and included additional questions	– 97% reported BPs were primary method of waste disposal, while 61% lived within ¼ mile of a BP – Respiratory symptoms increased from 20% pre-deployment to 95% post-deployment	– Lack of quantifiable data – Relied exclusively on self-reported exposure and outcome reporting, heavily susceptible to bias – Self-acknowledged pilot survey with small sample size

(continued)

TABLE III. (Continued)

First Author and Year	Study design	Site examined	Study population	Findings	Limitations
				– Shortness of breath with exercise increased from 5% pre-deployment to 87% post-deployment	

Abbreviations: AD, active duty; SM, service member; AHI, apnea–hypopnea index; AH&OBPR, Airborne Hazards & Open Burn Pit Registry; AOR, adjusted odds ratio; BP, burn pit; CI, confidence interval; CV, cardiovascular system; EIB, exercise-induced bronchoconstriction; IRR, incident rate ratio; JBB, Joint Base Balad, Iraq; LRT, lower respiratory tract; OIF, Operation Iraqi Freedom; OSA, obstructive sleep apnea; PSG, polysomnography; RR, relative risk; URT, upper respiratory tract.

increasing BP exposure, there was no significant increased risk of asthma or COPD/chronic bronchitis. However, patient-reported survey data did demonstrate a significant dose–response association between more days near BPs and a higher risk of COPD/chronic bronchitis ($P = .01$). A dose–response association between greater hours per day of BP exposure and a higher risk of COPD/chronic bronchitis ($P = .0005$) as well as hypertension ($P = .003$) was also observed. There was no significant association between BP exposure and an asthma diagnosis ($P = .15$).

Smith likewise used survey responses among a cohort drawn from the MCS but found no significant increased risk for newly reported emphysema/chronic bronchitis, asthma, or respiratory symptoms (defined as recurrent or persistent cough or dyspnea) when comparing those with and without BP exposure.[19] Subgroup analysis did reveal that deployment to JBB was associated with an increased risk for respiratory symptoms relative to other locations.

Lastly, a cross-sectional survey conducted by Poisson consisted of an online survey completed by 109 veterans, the vast majority of whom had used BPs as the primary means of waste disposal while deployed.[26] This survey showed a drastic increase in the rate of respiratory symptoms and specifically shortness of breath with exertion following deployment.

DISCUSSION

BP exposure amongst ADSM deployed to Southwest Asia (SWA), principally Iraq and Afghanistan, has gained national attention in recent years due to the increasing prevalence of chronic health problems among SMs in close proximity to BPs.[1,27,28] The effect of BP exposure on the RT has been central to these concerns due to the small particulate size, unregulated burning of inorganic and organic material, toxic smoke composition, and proven injurious effects of some of these airborne compounds in vitro.[7,8] BP smoke, for instance, has been found to contain particulate matter (PM_{10} and $PM_{2.5}$), lead, dioxins, mercury, furans, polycyclic aromatic hydrocarbons, and volatile organic compounds, many of which have been shown to induce inflammation and injury at the cellular and tissue level in laboratory experiments.[29] Yet, despite the widespread concern regarding potential impact of BP exposure on the health of tens of thousands of SMs and veterans, there have been relatively few studies examining this question. This systematic review demonstrated that, to date, only a handful of studies have directly examined the effect of BP exposure on the URT or LRT.

Despite the paucity of published data, there is more research available to interpret the effects of BP on the LRT. In this systematic review, all but one of the studies examined the effects of exposure on the LRT. Nevertheless, the conclusions varied and, due to the heterogeneous nature of the reported data, meta-analysis was not possible. Within the VA system, a significant positive dose–response relationship between BP exposure and patient-reported LRT diseases was identified. However, when exposure was analyzed against VA medical records, no significant association between exposure and objective evidence of LRT disease was appreciated. Three of the four studies that directly assessed effects of BP exposure on the LRT were large, high-powered retrospective cohort studies that used objective data to quantify BP exposure during deployment. Overall, there seems to be a higher incidence of self-reported LRT diseases among patients with BP exposure, although there are no objective data to suggest increased LRT diagnoses among these patients.

Additionally, another study included in this review demonstrated an increased rate of medical encounters for respiratory symptoms and asthma in OIF cohorts relative to a control cohort stationed in the USA, regardless of BP exposure. This would suggest at the very least that BP exposure alone may not be the sole agent leading to increased LRT outcomes. The finding that deployment to Iraq, not particular bases with BPs, is associated with higher rates of LRT medical encounters may substantiate the theory that other environmental exposures inherent to Iraq (e.g., dust, sand, and industrial fumes) could be associated with adverse RT outcomes as has been suggested previously in the literature.[30]

In contrast to these retrospective cohort studies, three of the prospective studies only peripherally examined the effects of BP exposure on their cohorts. Klein-Adams as well as Morris in STAMPEDE I collected survey data as a component of their studies demonstrating a high rate of BP exposure among their cohorts. In both studies, batteries of diagnostic tests were conducted with the aim of identifying EIB or diagnosing the cause of LRT symptoms. Despite gathering a large amount of objective data relating to the LRT, none of the data was correlated with the survey responses indicating BP exposure. Thus, limited conclusions can be drawn from these studies regarding the effect of BP exposure on LRT disease or symptoms.

Similarly, STAMPEDE III presents a rigorous diagnostic evaluation of SMs with LRT symptoms post-deployment and provides the most comprehensive data to date on the RT diagnoses most likely to be affecting this population. Of note, similar to the findings in STAMPEDE I, nearly a third of SMs remained undiagnosed at the conclusion of the evaluation with no etiology identified for their dyspnea, further corroborating the discordance between LRT symptom burden and objective findings in this population. Despite a wealth of information regarding the outcomes in question, however, there is a lack of detail presented regarding the exposure data that were collected; not only is there no correlation between exposure and outcomes data on a patient level, but the exposure data are only presented in aggregate means and not as a percentage of patients. Again, this limits the epidemiologic conclusions that can be drawn between exposure and outcome.

As inconclusive as the evidence for BP effects on LRT disease is, the data are even more lacking for the effects of BPs on the URT. This is particularly important because a growing body of evidence, described as the unified airway theory, has demonstrated similar pathophysiologic mechanisms for the LRT and URT as it relates to both allergic and non-allergic diseases.[31,32] Application of this model to SMs with BP exposure would suggest that the potential exists for chronic inflammatory diseases on the URT much like the LRT.

Furthermore, a well-conducted recent study of veterans with persistent respiratory symptoms showed a high prevalence of both LRT and URT diseases, including LRT conditions such as distal lung disease and asthma as well as URT conditions such as chronic rhinosinusitis and vocal cord dysfunction. Although this study did not examine any exposure data and was therefore excluded from our review, it does demonstrate a burden of both LRT and URT diseases in SMs who deployed to SWA.[33]

The findings of this systematic review are aligned with other previous reports. For instance, the largest BP historically was located at JBB in north-central Iraq, where several hundred tons of solid waste material were burned each day by 2007. Concern over exposure to this and other BPs led to multiple Congressional inquiries and eventually legislation mandating alternative means of waste disposal and the creation of a Veteran's Affairs Burn Pit Registry. More importantly, it initiated further study into the potential effects of BP exposure on the health of SMs. In 2011, the Institute of Medicine published *Long-Term Health Consequences of Exposure to Burn Pits in Iraq and Afghanistan*, which analyzed raw data from BPs, environmental sampling and previously unpublished DoD findings. Despite access to a vast trove of epidemiologic data and all research available in the literature, the study did not obtain any definitive conclusions aside from recommending further well-constructed research.[34]

This report was followed by the *Assessment of the Department of Veterans Affairs Airborne Hazards and Open Burn Pit Registry*, published by the National Academy of Sciences in 2017.[35] This report included several analyses of health outcomes based on reported BP exposure using registry data collected through March 2015. The outcome measures analyzed were limited to LRT and cardiovascular conditions and failed to address URT outcomes. Of the data that were analyzed, however, all self-reported health outcomes were found to have a statistically significant dose–response relationship with self-reported exposure, that is, increased relative risk of claiming the examined disease with increased exposure to BPs. There were notable caveats to these analyses: respondents consisted of a very small percentage of total deployed SMs, and the authors also noted strong positive associations between exposures and outcomes with no known scientific explanation. Nevertheless, these analyses did show an increased risk of self-reported adverse health outcomes with increased BP exposure.

Given these findings and the increasing attention devoted to the issue, the Department of Veterans Affairs commissioned the National Academies to form an expert committee specifically analyzing respiratory health outcomes in veterans of the conflicts in Iraq and the Middle East. Published in September 2020, *The Respiratory Health Effects of Airborne Hazards Exposures in the Southwest Asia Theater of Military Operations* is an exhaustive 233-page report analyzing respiratory outcomes of veterans of the current conflicts in SWA. The committee formed a list of 27 health outcomes related to both the URT and LRT and analyzed each outcome and its relation to airborne exposures while deployed based on all currently available evidence.

Of these, only respiratory symptoms (chronic persistent cough, wheezing, or shortness of breath) were deemed to have "limited evidence of an association". There was not enough evidence to determine if an association exists for the remaining outcomes. Although this report looked at all in-theater exposures and not specifically BP exposure, these findings correlate well with the results of our review: LRT symptoms appear to have a positive association with exposure, and existing research is on the whole inadequate with regard to RT health outcomes after deployment to SWA. When looking specifically at health outcomes after BP exposure, the committee determined that "existing research efforts on the health of theater personnel are inadequate to shed light on this question" and that further research efforts and new advances are needed.[36]

Despite the initial lack of data supporting disease association to BP exposure, but pursuant to Congressional mandate, US Central Command (CENTCOM) issued comprehensive BP guidance in 2009 generally limiting their use. However, as of August 2010, there were 251 active BPs in Afghanistan and 22 active BPs in Iraq. As late as 2013, many bases in Afghanistan continued to use open-air BPs for waste disposal despite policies mandating evaluation of alternative means.[37] Contrary to policies and legislation, the practice of solid waste disposal in open-air BPs with potential exposure to thousands of US SMs continues. As of March 2019, there were still nine open-air BPs in active use across the CENTCOM area of responsibility.[38] Therefore, those providing care for active and former SMs must remain aware of the potential for this exposure and any corresponding adverse health sequelae.

A central problem that has limited epidemiologic studies following deployment to SWA since 2001 is the difficulty in correlating health outcomes with specific exposures. This problem is particularly pronounced with health outcomes involving the RT given the multitude of potentially injurious exposures faced by SMs while deployed to SWA, including sand/dust, exhaust fumes, munitions discharges, and cigarette smoking in addition to BPs. For example, in all three studies in our review that gathered exposures data on sand/dust as well as BPs, there was a greater percentage of patients who reported a significant exposure to sand/dust than to BPs, which certainly presents a confounding variable when assessing any potential cause of RT outcomes. The 2011 Institute of Medicine report on BPs found that the particulate matter concentration at multiple U.S. bases was well above U.S. standards for $PM_{2.5}$ and PM_{10} and noted this was most likely due to ambient environmental conditions, that is, sand and dust. Prior studies including the Armed Forces Health Surveillance Study published in 2010 have demonstrated similarly high levels of geologic dusts as well as compounds consistent with BP emissions. Additionally, the role of increased tobacco consumption in deployed ADSM is a potentially confounding exposure, as prior studies have shown that the rate of tobacco consumption among deployed ADSM may be as high as twice the national average.[39,40]

An additional challenge facing researchers that is highlighted by our review is the heterogeneity of exposure and outcome data utilized in these studies. All prospective studies and several retrospective studies utilized survey responses to gather exposure data, which are susceptible to recall bias. Exposure data were also gathered in some studies simply by location of deployment, which risks combining individuals with varied levels of exposure into a single group for analysis. Outcomes data were both subjective (patient completed survey responses) and objective, which ranged from ICD-9 codes alone to patient-level clinical and diagnostic data. This widespread variance in reporting in the literature hinders the ability to synthesize data and draw epidemiologic conclusions regarding the effect of a specific exposure on a specific health outcome.

Our systematic review has limitations. As listed above, there are multiple other exposures faced by SMs while deployed that may contribute to adverse RT outcomes in addition to BP exposure, particularly high levels of dust/sand as well as tobacco consumption. Our review highlights the heterogeneity of the current data, to include varied methods of reporting both exposure and outcome, which prevents quantitative analysis and complicates interpretation of available data. Furthermore, the lack of objective individual-level exposure data weakens the strength of conclusions that can be drawn. Research examining BP exposure during the current conflicts is relatively sparse, although four of the nine total studies included in our review were published within the past year, suggesting the body of literature is growing. Prospective, multi-institutional studies examining both URT and LRT would better characterize the disease process and give a better understanding of the relationship between exposure and outcome. Lastly, long-term follow-up is necessary, as URT and LRT diseases may have significant latency and develop after many years.

CONCLUSION

Although the literature is sparse and definitive conclusions are limited by multiple airborne exposures and varied reporting measures, exposure to BPs may increase the incidence of self-reported diseases and symptoms of the LRT. There are no objective data to suggest that BP exposure leads to an increased rate of LRT diagnoses, although shorter follow-up times may not have allowed for full manifestation of long-term health sequelae. Furthermore, a paucity of data exist examining URT outcomes and BP exposure. Future prospective and multi-institutional studies should examine and characterize these possible relationships as well as investigate other airborne hazards related to deployment.

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