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Human survival in volcanic eruptions: Thermal injuries in pyroclastic surges, their causes, prognosis and emergency management

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ABSTRACT

This study of burns patients from two eruptions of Merapi volcano, Java, in 1994 and 2010, is the first detailed analysis to be reported of thermal injuries in a large series of hospitalised victims of pyroclastic surges, one of the most devastating phenomena in explosive eruptions. Emergency planners in volcanic crises in populated areas have to integrate the health sector into disaster management and be aware of the nature of the surge impacts and the types of burns victims to be expected in a worst scenario, potentially in numbers and in severity that would overwhelm normal treatment facilities. In our series, 106 patients from the two eruptions were treated in the same major hospital in Yogyakarta and a third of these survived. Seventy-eight per cent were admitted with over 40% TBSA (total body surface area) burns and around 80% of patients were suspected of having at least some degree of inhalation injury as well. Thirty five patients suffered over 80% TBSA burns and only one of these survived. Crucially, 45% of patients were in the 40–79% TBSA range, with most suspected of suffering from inhalation injury, for whom survival was most dependent on the hospital treatment they received. After reviewing the evidence from recent major eruptions and outlining the thermal hazards of surges, we relate the type and severity of the injuries of these patients to the temperatures and dynamics of the pyroclastic surges, as derived from the environmental impacts and associated eruption processes evaluated in our field surveys and interviews conducted by our multi-disciplinary team. Effective warnings, adequate evacuation measures, and political will are all essential in volcanic crises in populated areas to prevent future catastrophes on this scale.

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1. Introduction

Combating the human and economic losses of natural disasters is an ever-present global challenge to ensure that appropriate mitigation measures, such as warnings and evacuation responses, are in place to protect vulnerable populations. Hazardous volcanic eruptions are an important element of the global challenge [1], and yet their sporadic occurrence and the scarcity of study opportunities imposes limits on the available evidence base needed for an effective management of their human impacts. In addition, there is limited experience and mixed results in most volcanic areas of managing volcanic emergencies when eruptions are so uncommon. The main problem in decision-making lies in forecasting the type, magnitude and timing of destructive explosive eruptions, which may be fraught with uncertainty, even with high-quality scientific monitoring, and thus there is risk of evacuation being fatally delayed and incurring mass casualties suffering from severe thermal injuries. This paper summarises the experience from recent explosive eruptions, highlighting at Merapi volcano, Java, the hazards of unchecked population expansion in active volcanic regions, and the unique challenge volcanic disasters may present for emergency burns management.

Volcanism with its eruptions – violent fluxes of matter (magma) and energy (heat) – remains an integral part of the Earth's physical and biological evolution, as well as its planetary health. The global distribution of explosive volcanoes is typically related to where subduction zones exist within the grand scheme of plate tectonics where one crustal plate descends beneath another [2]. Accordingly, their greatest concentrations are found in countries around the Pacific Rim, including South and Central America, Mexico, western United States and the Aleutian arc, Kamchatka and the Kuriles, Japan and the Marianas, the Philippines, Indonesia, Melanesia, and Fiji to New Zealand. Other important clusters occur about the Mediterranean Sea, in Iceland and other islands in the Atlantic, and the West Indies [2]. Unrestricted development of settlements in regions of active volcanism is almost the norm in many of these countries, where even major cities can be at risk [3].

A wide range of human impacts may occur from the ash falls and lava flows that often accompany any eruption, but recent global eruptions confirm that pyroclastic density currents (PDCs) are the greatest threat to life [4] and thus the dominant hazard in planning for explosive volcanoes in populated areas [5]. A dilute pyroclastic density current (PDC), or surge, as we shall refer to the phenomenon here, is typically an intensely hot (200–400 °C), fast-moving cloud of fine ash and gases capable of causing devastation over wide areas extending from a few to tens of kilometres or more from the volcano [2]. Their destructiveness emanates from their high temperatures which can be extreme enough to cause built up areas to catch fire if ash gains entry to buildings and comes into contact with their combustible contents, especially when combined with the dynamic pressure of the surge front, a lateral force that can blow out openings, smash and topple structures [6].

The dense PDCs known as pyroclastic flows have undercurrents with high-particle concentrations that are almost invariably lethal to encounter, but there are examples of survival in encounters with surge eruptions and, in populated areas, mass burns casualties. With the current, rapid expansion of world populations in areas of active volcanism, this hazard needs to be more widely recognised, and hospitals prepared in the event of future volcanic crises.

The case history of the eruption at Merapi volcano, Java, in 2010 is a seminal 21st century eruption in this respect, with a population that had grown over a few decades to a million inhabitants spread over its flanks. During the course of the eruption, at least 400,000 of these were compelled to move [at very short notice] on the advice of the authorities and scientists monitoring the volcano [7,8]. Nonetheless, over 200 people died and many others suffered thermal injuries in the erupted PDCs. The rapid and unpredictable escalation of the activity of the volcano over 11 days necessitated a phased evacuation during this period, in line with the rapidly expanding area of hazard from pyroclastic flows and surges.

We describe here the largest series of hospital-treated volcanic burns casualties to date, as collated from this event and a smaller lethal eruption of Merapi in 1994, to illustrate the nature of the hazard so that a threatened population and their officials may prepare for the risk, and to draw the attention of the health sector to the severe thermal injuries that can occur and their likely prognosis. To provide contextual background to these two eruptions, we also briefly review the evidence of impacts in recent major surges at three other important volcanoes, beginning with a summary of our understanding of how surges cause thermal injury.

2. Background

Recent research has revealed that the deaths of most victims at Pompeii and Herculaneum (Italy), the two most famous archaeological sites in the world, were caused by pyroclastic surges formed in phases during the AD 79 eruption of Vesuvius, prior to the cities being completely buried under thick volcanic deposits [9]. During the 18th century excavations, archaeologists found a way of producing plaster casts of the spaces left by the decayed bodies of the victims interred in the eruption and, while adding to the pathos of the ruins of Pompeii, these provided invaluable clues on the last moments before life became abruptly extinguished there [10].

The pyroclastic surges at Vesuvius comprised fast-moving currents of hot, fragmented particles and gases (mainly entrained air) generated from collapses of the unstable eruption column of the AD 79 eruption [11,12]. Alternative mechanisms for surge generation, with their thermal impacts described below, include collapse of lava domes [13], laterally-directed blasts from lava domes, as in the present study at Merapi, 2010 [8], or magma stalled at very shallow depths and then depressurised, as at Mount St Helens in 1980 [14]. Their low-friction flow is mainly driven by gravity, and they can attain devastatingly high velocities.

The source process can influence the surge dynamics and the scale of phenomena, such as mass released, particle size distribution, mass flux, current velocity, dynamic pressure, and temperature. The source magma or recently-emplaced dome lava, is typically about 900–1000 °C, but the temperature