Rehabilitation of injured or ill Australian Defence Force (ADF) Members

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The Director of the ADF Rehabilitation Services, Mr Jim Porteous, presented this article at the Defence Health Symposium in Brisbane on 21 October 2006.

This article explains the purpose of rehabilitation in the ADF; building a seamless rehabilitation management process; the essence of best practice rehabilitation programs; and the outcomes we expect to achieve.

Purpose

In October 2004, we began redeveloping the ADF's rehabilitation system to enhance the management of members being rehabilitated, as well as meet the new legislative requirements of the *Military Rehabilitation and Compensation Act 2004* (MRCA). A Steering Committee, with representatives from the ADF and the Department of Veterans' Affairs (DVA), was formed to oversee the redevelopment of the rehabilitation system.

Clinical rehabilitation and a formal return to work (RTW) on restricted duties program have been provided for some time as part of medical treatment through ADF health facilities for illnesses and injury. Specific ADF units provided rehabilitation programs based on unit requirements. The primary drivers of rehabilitation to date have been Army units, due to their inherently higher physical demands and injury rates.

The ADF Rehabilitation Program (ADFRP) is much more than clinical treatment or health care of military personnel. It is an holistic assessment and management system that combines the elements of health care, occupational health and safety, and personnel capability management (Figure 1). Unlike the civilian sector, rehabilitation is provided to our military personnel regardless of whether the injury or illness is work related and compensable.
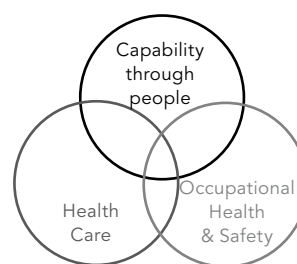

Figure 1. Alignment of purpose

From a health care perspective, the ADF has a responsibility to provide health care to its members in order to maintain the required level of operational readiness. Rehabilitation focuses on the restoration of physical and mental functioning. It is a key component for facilitating the return of members to a state of readiness (for deployment on a military mission) as soon as is practicable after injury or illness.

The new program has also been developed to ensure the ADF meets its duty of care to members and its responsibilities under the Commonwealth occupational health and safety legislation and the Military Rehabilitation and Compensation Act. As an occupational health and safety initiative, it seeks to reduce the impact of occupational injury, illness and disease, and to minimise the members' need for compensation.

Most importantly, the new program is workplace or occupational-based as this provides the most realistic environment to assess fitness for work. It focuses on the restoration of productive work functioning. Through rehabilitation more members of the ADF will be employable and deployable, resulting in an increase in military capability. In addition, effective rehabilitation will reduce the number of medical discharges.

We use a case manager to provide continuity of care throughout a member's rehabilitation through the timely provision of identified services and the coordinated participation of the member, health staff, command elements and rehabilitation decision-makers in the development and delivery of rehabilitation plans.

Through effective rehabilitation the ADF maximizes the personnel dimension of capability with the intent to return an injured or ill member to maximum effectiveness within the ADF environment, or if this is not possible, the civilian environment.

The purpose is to maximise the ADF's ability to fight and win by reducing the impact of occupational injury and illness.

Process overview

The new program involves early identification, treatment and management of injury or illness, through a coordinated response involving all relevant parties.

Triggers - Members, health staff and commanders at all levels have a responsibility to ensure that intervention through assessment occurs as soon as practicable after injury or illness. The requirement for a Rehabilitation Assessment is triggered when:

- A treating Medical Officer considers it necessary.

- A member is to be on sick leave/restricted duties/convalescence > 28 days.

- A member requests an assessment.

- A member's Commanding Officer requests an assessment.

- A needs assessment by the Military Rehabilitation and Compensation Commission recommends that rehabilitation may be beneficial.

Assessment – Rehabilitation must occur at the earliest possible time in order to optimise the outcomes. Wherever possible, rehabilitation will be workplace-based as this provides the most realistic environment to assess fitness for work.

Rehabilitation Plan – An important element of the Program is an individual's Rehabilitation Plan. It is aimed at returning injured or ill members to suitable ADF employment, or if appropriate, providing a seamless transition to the civilian environment. All Rehabilitation Plans commence with a thorough assessment of a member's suitability and capacity to undertake rehabilitation.

Outcome – The three goals of the ADFRP (in priority order) are:

Goal 1 – Fit for duty in the pre injury/illness work environment.

Goal 2 – Fit for duty in a different position and/or environment.

Goal 3 – Transition out of the ADF with the optimal level of function.

Building a seamless rehabilitation process

Rehabilitation is a multi-disciplinary strategy to maximise an individual's potential for restoration to their pre-injury physical, vocational, social, psychological and educational status (Figure 2). It is much more than clinical management.

Figure 2. *Multi-disciplinary seamless rehabilitation strategy*

Member – When examining the various elements of the ADFRP, we start with the military member as the central element. They have a responsibility to maintain their fitness and ability to deploy on overseas operations, and we want to support, rehabilitate and retain them.

Health Care – Is focused on the achievement of optimal physical and mental recovery.

Compensation and the Transition Management Service (TMS) – Through compensation eligible ADF members may be provided with financial compensation, payment of travel to attend medical appointments, home and car modifications, household services and attendant care at home. In addition, DVA provides transition management services that prepare all members being discharged on medical grounds for civilian life.

Command – The focus of this element is on return to suitable work at the earliest possible time. Service Chiefs are responsible for the prevention and management of work-related injury and illness. Commanders and supervisors are responsible for the health and welfare of members under their command. This includes the provision of a safe workplace and

the maintenance of personnel fitness, occupational and military skills, and career management.

Psychosocial - Restoring the individual's ability to function in the community and their confidence to participate and take control of their rehabilitation.

Case management and coordination - The ADF Rehabilitation Coordinators are responsible for the contracting and coordination of contracted rehabilitation case managers. They support commanders and supervisors in coordinating the rehabilitation of their people, together with Health and Personnel agencies.

Examining the essence of best practice Rehabilitation Programs

One of the many studies that provided the essence of best practice was the 2004 "Workplace-based Return to Work Interventions: A Systematic Review of Quantitative and Qualitative Literature" study by the Canadian Institute for Work and Health. They made a number of recommendations in relation to successful injury management and rehabilitation interventions. These are:

- All workplace-based return to work (RTW) strategies include early contact with the worker by the workplace, a work modification offer, and contact between the workplace and healthcare providers;

- Workplace-based RTW strategies include a strong ergonomic component, as facilitated by ergonomic workplace visits;

- Education for supervisors and managers as part of the interventions;

- Building the confidence in the rehabilitation process and a shared understanding among all parties (injured person, supervisor, physicians and insurance providers), and gaining their commitment;

- Providing adequate and consistent information (including rights and obligations) when communicating with the injured person about return to work;

- Creativity and sensitivity to the needs of all parties be considered an integral part of modified work planning;

- There is careful coordination and consideration of the needs of all parties, and that the feasibility of rehabilitation plans and the ability of the person to successfully negotiate the process is addressed;

- Supervisors are important to the process and are included in RTW planning and offered related training; and

- Rehabilitation and occupational healthcare experts are involved in the process as they are a bridge between the workplace and healthcare providers.

From our experience, these were essential to the development and the successful implementation of our program.

The ADF Rehabilitation Program involves early identification, treatment and management of injury or illness, through a coordinated response involving all relevant parties, in order to reduce the likelihood of an injury or disease becoming a long-term injury or illness. Wherever possible, rehabilitation should be workplace-based as this provides the most realistic environment to assess fitness for work.

An important element of the program is an individual's Rehabilitation Plan. This is a managed process involving early intervention with appropriate, adequate and timely services based on assessed needs. It is aimed at returning injured or ill members to suitable ADF employment, or if appropriate, providing a transition to the civilian environment.

The principles of the ADFRP are:

a. Early intervention to reduce the impact of injury, illness and disease and contribute to enhanced capability.

b. Utilisation of evidence based process to establish clear and accurate expectations of the outcome of rehabilitation and reduce psychosocial complications.

c. Rehabilitation assessments and plans based on an individual's needs and the inherent requirements of service.

d. Coordinated participation of the member, health staff, command elements and rehabilitation decision-makers in the development and execution of rehabilitation plans.

e. Maximising the potential for a positive rehabilitation outcome for the individual, ADF and the community.

f. Clear roles and responsibilities reflected in organisational performance agreements combined with accountability as measured against the performance indicators of the Services and Groups.

The principles of the ADF Rehabilitation Program have been developed to suit our Defence Force. And they are based on best practice programs.

Outcomes

We have developed our new program as a strategic initiative that will contribute to the following outcomes:

Increased Capability – Increase the ADF's capability by reducing Workdays Lost Through Injury, as well as support the retention of experience through reduced separations. The aim of the Program is to return all members to duty, either in their pre-injury role or in a new role identified as part of their rehabilitation.

Support Retention – Reduce the number of separations through fewer medical discharges, thereby saving the ADF many millions of dollars a year in separation costs.

An Employer of Choice – Support the ADF in meeting its duty of care thereby enhancing its reputation in the community as an employer of choice where 'people matter'.

Continuity of Care – Dedicated case management for members requiring rehabilitation will coordinate the support of the Chain-of-Command, Health and Personnel services and if required, Department of Veterans' Affairs. Case management will also provide continuous support for members requiring transition to civilian life.

OHS Strategic Plan – Priority 3 is to "Reduce the impact of occupational injury, illness and disease".

Early Intervention – Provide rehabilitation programs based on early intervention and focusing on the physical, mental and occupational rehabilitation of members.

Legal Compliance – Support the ADF in meeting its legal obligations under the Defence Act 1903, OH&S Act 1991, the Safety, Rehabilitation and Compensation Act 1988, and the Military Rehabilitation and Compensation Act, 2004.

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What is the effectiveness of lung assist devices in blast lung injury: A literature review

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Abstract

Blast lung injury (BLI) is a direct consequence of a blast wave from high explosive detonations upon the body. The physics of a blast wave are nonlinear and complex. The primary blast effects are most significant at air-fluid interfaces such as the ear, lung and gastrointestinal tract. Of these air-fluid containing organs, the lung is most susceptible to the primary blast effects and the extent of lung injury is considered a decisive parameter in defining morbidity and mortality for blast victims both at the scene and among initial survivors. The clinical sequel of BLI is a rapid respiratory deterioration and progressive hypoxia with resultant ventilation perfusion mismatch and subsequent acute respiratory distress syndrome (ARDS). All patients with significant BLI require mechanical ventilation and admission to ICU. The rationale for using the LAD in BLI is not primarily to improve oxygenation, but more to minimise ventilator associated lung injury, and to ameliorate and eliminate the inflammatory process that is enhanced by mechanical ventilation. The notion of a lung assist device (LAD) was first raised in 1967 by Rashkind who proposed a pumpless oxygenator for temporary lung assist in cystic fibrosis, ARDS and congenital heart disease. The aim of this paper is to identify through an extensive literature review: (1) the effectiveness of LAD in BLI; and (2) the recommended treatment modalities for BLI. This paper will also provide current information ensuring that medical and nursing staff within the Australian critical care setting become familiar with the management of BLI.

Introduction

Blast lung injury (BLI) presents a unique triage, diagnostic and management challenge for health professionals working in critical care. BLI is a condition that is seen most frequently in a combat or military environment, however, urban terrorist activities such as the recent Bali, Madrid and London train bombings, plus industrial and domestic explosions can occur at any moment in the civilian setting. BLI is a direct consequence of a blast wave from high explosive detonations upon the body. The physics of blast waves is nonlinear and complex.[1] The blast wave consists of two parts, a shock wave of high pressure followed closely by a blast wind, or air in motion.[2] The effects of blasts fall into the following four categories: primary (direct effects of pressure), secondary (effects of projectiles), tertiary (effects due to wind), and quaternary (burns, asphyxia, and exposure to toxic inhalants).[1] Primary blast injuries are estimated to contribute to 47-57% of the injuries in survivors and 86% of fatal injuries.[3] The primary blast effects are most significant at air-fluid interfaces such as the ear, lung and gastrointestinal tract. Of these air-fluid containing organs, the lung is most susceptible to the primary blast effects and the extent of lung injury is considered a decisive parameter in defining morbidity and mortality for blast victims both at the scene and among initial survivors.[4, 5]

BLI is characterised by the clinical triad of (1) apnea, (2) bradycardia, and (3) hypotension and may occur without obvious external injury to the chest.[5] Additionally, the blast waves' impact upon the lung results in tearing, haemorrhage, contusion, and oedema. The clinical sequel of BLI is a rapid respiratory deterioration and progressive hypoxia with resultant ventilation perfusion mismatch and subsequent acute respiratory distress syndrome (ARDS).[3,6,7] The rapid ARDS picture that develops in BLI patients is a direct result of the high pressure wave front passing through the interfaces between air, alveolar, tissue and blood vessels. This pressure front causes chest wall displacement toward the spinal column, leading to transient high intrathoracic pressure. The elevated intrathoracic pressure leads to tearing of the alveolar septa, stripping of airway epithelium, and rupture of alveolar spaces with consequent alveolar hemorrhage, edema, and alveolovenous fistulae.[7,8] Currently, there is no standardised assessment criteria for the diagnosis of BLI, however, is typically confirmed by clinicians from the following: chest radiographs showing a butterfly appearance (with or without pneumothorax) on admission and increased haziness in serial chest radiographs; the presence of burn injuries; and smoke inhalation of the upper airways as seen at bronchoscopy.

Interventional Lung Assist Devices

The notion of a lung assist device (LAD) was first raised in 1967 by Rashkind *et al*[9] who proposed a pumpless oxygenator for temporary lung assist in cystic fibrosis, ARDS and congenital heart disease. This vision could not be realised with the technologies available at the time; however, over the past decades critical care medicine has made tremendous contributions to improve outcomes in patients suffering from acute lung injury (ALI).[10] Key technologies for LAD include diffusion membranes to avoid plasma leakage in prolonged applications, long-term coating technologies and homogeneous distribution of blood flow. Currently, three concepts for LAD are being explored: (1) Interventional LAD for percutaneous attachment to the systemic circulation creating an arteriovenous shunt. This device is for single use and does not require a blood pump due to its insertion into the femoral artery and vein; (2) Intravascular gas exchange devices for single-needle venous access have been designed for implantation in the vena cava or the pulmonary artery. A pulsating balloon in the membrane bundle or an impeller blood pump can be employed to optimise blood flow around the gas exchange fibers or across the device; and (3) Total artificial lungs to completely replace pulmonary gas exchange function.[11] LAD are viewed as an adjunct to mechanical ventilation that allow for optimised lung protective ventilation, thus giving the lungs time to heal and provide a bridge to recovery, or a bridge to transplantation after acute lung injury. Dembinski *et al*[12] tested the safety and efficacy of a LAD (Delta Stream Rotary Blood Pump) in a controlled trial on animals with experimental ALI. The results from this study showed that in animals (N = six pigs) with ALI, hoemodynamics remained stable and gas transfer across the LAD was optimal with two animals showing a marked increase in PaO_2 and carbon dioxide (CO_2) removal was effective in all animals. Although the results from this study cannot be generalised to all ALI they give an insight into the potential benefits that LAD pose in treating ALI and BLI.

Impetus for the literature review

During the period March till July 2005 at the 332nd Expeditionary Medical Group (EMDG), a United States Air Force Hospital (USAF) based in Iraq, several patients suffering severe BLI due to improvised explosive devices (IED) were treated. The management of these patients within the intensive

care unit (ICU) became extremely difficult as they developed permissive hypercapnia, severe acidosis and ARDS. To prevent further deterioration and minimise ventilator induced lung injury these patients were trialed on an interventional LAD called the NovaLung.® This device showed promising results with significant improvements seen in patients' acidosis, oxygenation and reduced ventilator support. Consequently, these improvements enabled the patients to be aeromedical evacuated to a level four military hospital in Germany. The trials conducted at the 332nd EMDG have not been formally reported in the literature; however it is suggested that timely diagnosis and correct treatment of BLI will result in improved outcomes.[13]

Aims

The aim of this paper is to identify through an extensive literature review: (1) the effectiveness of lung assist devices in blast lung injury; (2) the recommended treatment modalities for BLI; and (3) that this paper will provide current information ensuring medical and nursing staff within the Australian critical care setting become familiar with the management of BLI.

Review process

Literature on lung assist devices and treatment modalities for BLI in the critical care setting from January 1995 until March 2006 was reviewed using the CINAHL, MEDLINE, Cochrane Library, Blackwell Synergy, and ProQuest databases. Key words utilised were: blast lung injury, acute lung injury, blast lung, barotrauma, lung assist devices, trauma management, treatment modalities, acute respiratory distress syndrome and extracorporeal membrane oxygenation. Combinations of these words were also used (e.g. lung assist devices – blast lung, acute respiratory distress syndrome – lung assist device, extracorporeal membrane oxygenation – blast lung, treatment modalities – blast lung). The lack of research conducted in this area was demonstrated by the fact that the review produced no primary source articles reporting the use of lung assist devices in blast injured patients. Consequently, the review process was broadened to incorporated all research conducted on subjects with injuries that would reflect a blast lung type injury (e.g. ALI, ARDS, and barotrauma). This broadening of the review process identified only three relevant primary source articles reporting the use of LAD for ALI/ARDS in clinical trials and three retrospective case studies of BLI patients. This paper reviews these articles and Table 1 displays the authors, design, sample and main findings of the reviewed articles.

Literature review

What is the effectiveness of lung assist devices in blast injured patients?

The articles reviewed indicated that lung injury developing within 24 hours after an explosion is typically classified as ARDS or ALI, depending on the severity of injury.[13] The three retrospective BLI case studies reviewed indicate that despite the severe hypoxemia caused by explosions, timely diagnosis and correct treatment will result in improved outcomes.[8,13] Furthermore, Avidan et al[8] was the only retrospective study to follow up the long term outcome of his cohort. Of the 28 survivors (one patient died 24 hrs after admission from sepsis and multiorgan failure), 75% responded to their telephone interview (median time of follow up was three years). This follow up reported that sixteen patients (76%) were free of respiratory symptoms and only five patients (24%) reported some degree of respiratory dysfunction leading them to conclude that BLI will have good outcomes if treated promptly and correctly.[8]

Clinical classification of BLI

Initiating the appropriate treatment for patients with BLI is dependent upon the severity of the blast injury and correct diagnosis. In assessing the presenting symptoms of BLI, Pizov et al[14] attempted to develop a BLI severity score and suggests that stratification of the severity of lung injury produced by blasts may be useful in the treatment and prediction of patient outcomes. The proposed BLI severity score is based on three objective signs: hypoxemia (PaO_2/FiO_2 ratio), chest radiograph findings, and the presence of bronchopleural fistula. The score defined three levels of injury: (1) Mild: PaO_2/FiO_2 ratio >200 mmHg, localised lung infiltrates and no pneumothorax; (2) Moderate: PaO_2/FiO_2 ratio of 60 to 200 mmHg and diffuse (bilateral/unilateral) lung infiltrates with or without pneumothorax; and (3) Severe BLI: PaO_2/FiO_2 ratio < 60 mmHg, bilateral lung infiltrates and bronchopleural fistula. Hypoxia exists in all patients with BLI and both Pizov et al[14] and Sorkine et al[13] have incorporated this objective measure into their lung injury scores. In Sorkine et al[13] retrospective analysis patients were assigned lung injury scores (LIS) according to the criteria of Murray et al.[15] The Murray score is a scale of 0 to 4 for four parameters: (1) evaluation of chest radiographs, (2) PaO_2/FiO_2 ratio, (3) level of positive end expiratory pressure (PEEP), and (4) lung compliance. The LIS was obtained through modification of the Murray score by adding individual criteria scores and dividing the sum by the number of variables used: no injury = 0, mild to moderate = 0.1 to 2.5, severe > 2.5, and maximal

Table 1. *Lung assist devices in ARDS and ALI, BLI case studies*

Author(s)	Year	Design	Sample	Main Findings
Ruettiman et al[20]	2006	Case study	N=1 (15 year old girl with MODS, ARDS) N=29 patients with BLI and required ICU admission.	* An arteriovenous pumpless extracorporeal LAD assisted in decreasing $PaCO_2$ and reduced mechanical stress by applying minimal MV; * LAD was simple to operate and has potential for routine use in treatment of ARDS.
Avidan et al[8]	2005	Retrospective study	N=1 (male fire eater, aspirated on paraffin oil – ARDS)	* 76% of patients required MV (mean 11.4 days); * Aids/special modes of MV included HFJV, NO; * Long term outcomes of 28 survivors (75% responded to interview) 76% nil symptoms, 24% with respiratory dysfunction; * PCV failed to improve oxygenation, hypercapnia and severe acidosis developed.
David et al[19]	2004	Case study	N=20 (41+/- 16 yrs) with ARDS and failing conventional therapy (i.e. surfactant replacement, prone positioning)	* HFJV improved PaO_2 but not acidosis; * NovaLung™ enabled less aggressive ventilation, $PaCO_2$ normalised after initiation; * After six days, patient transferred to conventional MV, and ILA ceased at day 13.
Liebold et al[18]	2000	Prospective, controlled study	N=15 patients (median ages 29 years) with primary BLI resulting from explosions on two civilian buses in 1996	* After 24 hours of being connected to MO (Quadrox Special™, Jostra Inc) significant improvement in oxygenation ($p < 0.05$); * 15 patients weaned off MO, five patients died on system, 60% (12 of 20) survived procedure and discharged; * Simple system facilitating easier nursing care and fewer risks of technical complications.
Pizov et al[14]	1999	Retrospective study (BLI score developed retrospectively - modified Murray Score)	N=17 (11 male, 6 female) with severe pulmonary blast injury.	* Stratification of BLI severity may be used in future studies of BLI patients and guide appropriate management (use in triage) and serve to predict the final outcome; * severity of primary blast had dominant effect on development of ARDS; * all three patients with severe BLI who survived the first 24 hr developed ARDS as did 33% of moderate BLI, no mild BLI patients developed lung injury.
Sorkine et al[13]	1998	Retrospective study	three major bomb incidents in Tel Aviv from 1994 to 1996	* four patients developed increasing $PaCO_2$ levels (to 93+/- 12 mmHg) associated with a reduction in arterial pH that was corrected by increasing MV RR; * Evidence of ventilator induced pulmonary barotraumas; * 88% survived, 12% died from severe penetrating head injuries; * limited PIP in VCV is a useful and safe mode of MV in BLI patients

Key: MODS- multi-organ dysfunction, MV- mechanical ventilation, ARDS- acute respiratory distress syndrome, LAD – lung assist device, BLI – blast lung injury, ILA- interventional lung assist device, HFJV- high frequency jet ventilation, MV – mechanical ventilation, PCV – pressure controlled ventilation, MO- membrane oxygenator, VCV- volume controlled ventilation, RR – respiratory rate.

score = 4.0. On admission, the LIS for Sorkine et al[13] patient group was 3.2 +/- 0.3 indicating major lung injury while Pizov et al14 group showed 33% with mild BLI, 40% had moderate, and 27% had severe BLI. Pizov et al[14] criticises this modified Murray score or LIS because when applied to his patient group at 6 and 24 hours as it did not differentiate between patients with moderate BLI and those with severe BLI. Moreover, Pizov et al[14] argues that the most critical and dynamic period in which primary blast lung injury develops is during the first 24 hours. However, 24 hours post blast injury Pizov et al[14] study demonstrated good correlation between the proposed BLI score and the modified Murray score. The reliability and validity of both the BLI severity scoring system and LIS has not been established and its application in Pizov et al[14] and Sorkine et al[13] studies are limited due to the small sample size and retrospective analysis. Regrettably, Avidan et al[8] was not able to retrospectively apply the Murray score or any other measure of injury severity due to the failure of the hospital to hold a trauma registry and the lack of relevant data in patient charts. Therefore, the comparability of this study is questionable despite that it represents the largest reported series of blast lung injuries in the literature to date.

BLI patient management and treatment modalities

In the retrospective study conducted by Pizov et al[14] following primary resuscitation or surgery all patients with primary BLI (N=15) were admitted to the ICU. Similarly, in the Avidan et al[8] study of BLI patients (N=29) all required ICU admission. Although all the patients included in the Avidan et al[8] study were admitted to ICU, the authors acknowledge that a BLI patient may have been admitted to a ward bed and they were unable to retrospectively identify patients in this category. Additionally, even though the Sorkine et al[13] study group of blast lung injured patients (N=17) were all admitted to ICU, they represented only 5.6% of the total number of casualties injured during three bomb blasts in Tel Aviv. All three of the retrospective studies had similar distributions in the mechanism of lung injury with N=24 (83%) patients reviewed in Avidan et al[8] study injured in a closed space (defined as a bus or café); N=10 (59%) of patients in Sorkine et al[13] study were victims of an explosion in a bus; and all of the patients within the Pizov et al[14] study were in two civilian bus explosions.

Analysis of BLI patient records across all three retrospective studies revealed that to correct hypoxaemia and respiratory distress endotracheal intubation and mechanical ventilation was initiated either at the scene, during initial resuscitation in the emergency department, in the operating theatre, or in the ICU. In the Avidan et al[8] study, 22 patients (76%) required intubation and mechanical ventilation, 14 patients (93%) in the Pizov et al[14] study and 17 patients (100%) in the Sorkine et al[13] retrospective study. Sorkine et al[13] notes that in ARDS cases caused by other means, the large area of ruptured lung in BLI patients makes them prone to develop unique complications from mechanical ventilation. Furthermore, positive pressure ventilation and PEEP should be avoided whenever possible because of the risk of pulmonary alveolar rupture and subsequent arterial air embolism.[14] Air embolisms were clinically suspected in two patients (7%) in the Avidan et al[8] study, however, the mode of ventilation, level of PEEP, and outcomes of these patients is not documented in the results. In the Pizov et al[14] study of the five patients with mild BLI, one received oxygen through a face mask whereas the others received volume-controlled (VCV) or pressure support ventilation (PSV) with PEEP that did not exceed 5 cm H_2O. Of the six patients with moderate BLI two were ventilated with VCV and four with pressure controlled inverse-ratio ventilation (PCIRV) and received PEEP levels up to 15 cm H_2O.[14] Similarly, the levels of PEEP in the Avidan et al[8] cohort ranged from 0 to 15 cm H_2O (median 7.5 cm H_2O). It is impossible to compare this with the Sorkine et al[13] study as the results makes no reference to the PEEP levels used in the mechanical ventilation of its patients.

A possible explanation for this lack of data in the Sorkine et al[13] study is that he used a respiratory management strategy based on volume controlled synchronised intermittent mandatory ventilation (VC-SIMV) with small tidal volumes (V_T) and low peak inspiratory pressures (PIP) together with permissive hypercapnia. In limiting PIP through reduced V_T, the authors argue that ventilator induced lung damage is reduce. Furthermore, permissive hypercapnia which results in alveolar hypoventilation, respiratory acidosis, and lower ventilatory pressures may limit pulmonary over distension in severe lung injury.[13] The initial mechanical ventilation variables for the 17 patients in this study were a V_T of 6.4 +/- 0.6 ml/kg and a mandatory ventilator respiratory rate of 17 +/- 5 bpm, resulting in PIP of 35 +/- 0.3 cm H_2O.[13] Shortly after instituting mechanical ventilation with limited V_T, four patients developed elevated $PaCO_2$ (93 +/- 12.4 mmHg) which resulted in an associated reduction in arterial pH (7.13 +/- 0.08). Until this time Sorkine et al[13] made no attempt to control $PaCO_2$ levels until the arterial pH fell below 7.20, at which time the mandatory respiratory rate was increased in increments of two breaths per minute until the pH rose to greater than 7.50. These low pH values

responded to the increased respiratory rate and Sorkine et al[13] state that the patients experienced no adverse metabolic or haemodynamic effects as measured by changes in mean arterial pressure (MAP), cardiac index (CI), central venous pressure (CVP), or peripheral vascular resistance (PVR). Of the 17 patients, two patients (12%) died while in ICU from severe penetrating head injuries. Despite the authors' assurances that there was no organ system dysfunction related to the respiratory acidosis they have not outlined which statistical tool was used to measure the significance level in these baseline physiological measures. Therefore, due to the lack of controlled studies utilising this ventilatory strategy the conclusions made by Sorkine et al[13] should be viewed cautiously.

Special modes of ventilation or unconventional therapies were applied in both Pizov et al[14] and Avidan et al[8] more severely lung injured patients. In the Pizov et al[14] study four severe BLI patients developed extreme hypoxia ($PaO_2/FiO_2 < 60$ mmHg) together with bronchopleural fistulae resulting in the following management: independent lung ventilation (one patient), extracorporeal membrane oxygenation (ECMO) (one patient), and a combination of nitric oxide (NO) inhalation and high frequency jet ventilation (HFJV) (two patients). Similarly, three patients in the Avidan et al[8] study were trialed on HFJV (two patients), NO inhalation (one patient) and excluding the patient trialed on ECMO, both studies patients' oxygenation improved, flow reduced through the bronchopleural fistula and lower ventilation pressures were required. Although NO has become increasing popular for the treatment of severe ARDS, it is not the first choice for treatment of hypoxaemia in lung injury.[16] Moreover, only three BLI patients were treated with NO making it impossible to draw any conclusions from the results of these studies. Pizov et al[14] states that HFJV is recommended for ventilation of patients with bronchopleural fistula, however, most clinicians would argue that they can be ventilated adequately with conventional mechanical ventilation.[17] Despite this argument, the results from these studies demonstrated that four patients with severe BLI (two with a bronchopleural fistula) were successfully ventilated with HFJV. As with patients treated with NO, no direct correlation can be made in regards to the effectiveness of HFJV and improved outcomes of severely lung injured patients due to the small sample size of the studies and the significance of its combination with NO in the Pizov et al[14] study. The patient in the Avidan et al[8] study trialed on ECMO two hours after the explosion experienced severe refractory hypoxaemia, shock, massive haemoptysis, and intrapulmonary bleeding increased upon heparin administration. Ultimately this patient died and the use of ECMO as

a last resort in a severely BLI patient was stated by Avidan et al.[8] Regrettably, the authors did not detail the type of ECMO device used or how it was managed in combination with mechanical ventilation.

Effectiveness of LAD in ARDS and ALI

The prospective study conducted by Liebold et al[18] was the first clinical report on the use of LAD applied to patients suffering from severe ARDS. Patients were selected for this study based on the consensus that if pulmonary injury could not be reversed the patient would die. Consequently, 20 patients (aged 41 +/- 16 years) with ARDS and failing conventional respiratory therapy (HFJV, surfactant replacement, prone positioning) were recruited through referral to either a cardiothoracic, surgical or medical ICU. The minimum heamodynamic requirements for inclusion in this study were a cardiac output (CO) > 6 L/min, and MAP > 70 mmHg which resulted in septic and cardiac failure patients being excluded from the study group. The authors aim was to test the feasibility and effectiveness of a pumpless extracorporeal LAD in patients with ARDS.[18] Liebold et al[18] justified the use of the pumpless membrane oxygenator (MO) (Quadrox Spezial™, Jostra Inc., Hirrlingen, Germany) because it is based on heparin coated hollow fibre technology thereby reducing the requirements for systemic anticoagulation, the risk of thrombus formation, and haemolysis of blood through a mechanical pump.

Similarly, the studies conducted by David and Heinrichs[19] and Reuttimann et al[20] are both a case report of a patient with severe ARDS who are trialed on the same pumpless interventional LAD (NovaLung™, GmbH, Hechingen, Germany). The similarities between these studies ceases there as David et al[19] utilises the LAD in combination with high frequency oscillatory ventilation (or HFJV), Reuttimann et al[20] aimed for apneic ventilation, while Liebold et al[18] reduced mechanical ventilation to achieve a more normal inspiratory: expiratory (I:E) ratio, reduced PEEP, and a reduced maximum airway pressure (Pmax). The mechanism of injury for each patient which resulted in the development of ARDS in these studies also varies dramatically. All Liebold et al[18] patients' developed ARDS from differing causes (e.g. pneumonia, lung contusion) while Reuttimann et al[20] case report details the treatment a 15 year old girl who fell 15 metres down a rock face and developed severe ARDS two weeks into her admission following a bacterial pneumonia. In contrast, David et al[19] reports on a 30 year old male who aspirated paraffin oil whilst fire eating, and rapidly developed hypoxaemia and ARDS (within eight hours). Initially, David et al[19] trialed pressure controlled ventilation (PCV), with PEEP levels increased to 20 cm H_2O, mean airway pressures of 27 cm H_2O, and despite repeated recruitment maneuvres, oxygenation did not improve

(PaO_2/FiO_2= 72 mmHg). Following this deterioration, the David *et al*[19] patient was commenced on HFJV to allow the application of a constant high mean airway pressure, avoid high cyclic inspiratory pressures, and end-expiratory lung collapse with reopening on inspiration. Within 24 hours, the $PaCO_2$ did not increase with concomitant respiratory acidosis (arterial pH 7.14) and neither lower oscillatory frequencies nor maximum amplitudes lowered the $PaCO_2$. Consequently, the authors decided to initiate the LAD to remove the carbon dioxide, correct the acidosis and offer less aggressive ventilation with HFJV. Similarly, Reuttimann *et al*[20] trialed PCV, with a high respiratory rate and low V_T, prone positioning, inhaled bronchodilators, high levels of PEEP, and inhaled NO but the patient remained critically hypoxaemic (PaO_2/FiO_2= 60 mmHg) and the $PaCO_2$ reached 145 mmHg. At this point the authors believed all conventional therapeutic efforts were exhausted; hence they initiated the pumpless LAD.

The David *et al*[19] results indicate that there was no further improvement in oxygenation after the LAD was started, however, CO_2 removal was effective and the arterial pH rose to 7.22 (from 7.14). Subsequently, to ensure sufficient blood flow through the membrane, the patients' CI was supported with inotropes (norepinephrine: max dose 1.5 mcg/kg/min) to achieve a flow of 2.5 L/min/m2. Once this flow was achieved the FiO_2 was reduced stepwise and at day 13 the LAD was removed. In a similar time frame, the LAD in the Reuttimann *et al*[20] case study remained in situ for 10 days, with the FiO_2 progressively weaned from 1.0 to 7.0 (day 5), then to 0.4 (day 10). Following 24 hours on the pumpless MO, Liebold *et al* reported significant improvement in oxygenation ($p < 0.05$), with MO therapy discontinued as soon as patients were stable for 24 hours (PaO_2 > 80 mmHg, FiO_2 < 0.5). A total of 15 patients were successfully weaned off the MO (median assist time being 12 +/- 8 days), while five patients died on the system (four from sepsis, one from VF arrest). A further three patients died after successful weaning on day 8, 30, and 50, respectively resulting in a overall survival rate of 60%.[18] Throughout this study, Liebold *et al*[18] experienced several technical problems including: thrombosis of the venous cannula (n = 5), thrombus formation within the MO (n = 2), MO plasma leakage (n = 2), and MO contaminated with Candida albicans. Due to these complications, the authors were forced to replace four MO (three MO had been running continuously for 22, 27, and 32 days) and no interruption in therapy was observed. Despite the drastically reduced sample size, both Reuttimann *et al*[20] and the David *et al*[19] results showed a survival rate of 100% plus they experienced no adverse effects during treatment with the LAD despite the David *et al*[19] patient having a reduced systemic anticoagulation for a percutaneous tracheostomy on day 12.

Conclusion

The paucity of controlled trials investigating the effectiveness of LAD in BLI patients is of great concern as the current global war on terror places both military and civilian personnel at an increased risk of exposure to a terrorist bombing event. Moreover, in the Australian critical care setting very few clinicians employed in trauma centres have any experience in both triaging and managing a severely BLI patient. The current assessment instruments for diagnosing the severity of BLI require further validation, however, are based on sound objective data and may assist in early management and triage. Treatment modalities of BLI should focus on correcting the effects of barotruama and supporting gas exchange. All patients with significant BLI require mechanical ventilation and admission to the ICU. Respiratory management of patients with severe BLI is challenging not only because of the lung injury (contusion, bronchopleural fistula), but also because it is often accompanied by shock and unconsciousness. Despite the risks associated with mechanical ventilation it remains the primary treatment modality for BLI patients. The literature indicates that current strategy for mechanical ventilation in BLI is to prevent further lung injury through a volume controlled synchronised intermittent mandatory ventilation with small tidal volumes (< 6ml/kg) and low PIP (< 40 cm H_2O) together with permissive hypercapnia (maintain pH > 7.2, $PaCO_2$ 56mmHg +/- 3.0). Complications of positive pressure mechanical ventilation and of higher PEEP levels in BLI patients are air emboli through the alveolovenous fistulae and pneumothorax. The rationale for using the LAD in BLI is not primarily to improve oxygenation, but more to minimise ventilator associated lung injury, and to ameliorate and eliminate the inflammatory process that is enhanced by mechanical ventilation. Regrettably, all the authors who have reported initiating the LAD have done so as a last resort (i.e. patient will die) when all other conventional and unconventional treatments have failed. Therefore, it is recommended that future research focuses on the following: (1) developing a valid and reliable BLI scoring system; (2) initiating an interventional lung assist device during the ALI phase (i.e. before ARDS develops); and (3) educating clinicians within the Australian critical care setting of the clinical sequel of BLI and the management of a mass casualty situation involving a terrorist bomb event.

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