2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) | 979-8-3503-2447-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/EMBC40787.2023.10340965

Can We Miniaturize CT Technology for a Successful Mobile Stroke Unit Roll-Out?

K. Cowell, T. Y. Pang, J. S. Kwok, C. McCrowe, F. Langenberg, D. Easton, C. Williams, S. M. Davis,
G. A. Donnan, H. De Aizpurua, A. Balabanski, A. Dos Santos, K. Fox

***Abstract*—Mortality from stroke remains high in Australia, especially for patients located outside the metropolitan cities. This is because they have limited access to specialized stroke facilities for optimal stroke treatment. Mobile stroke units have the capability to take CT scanners out to the patient however current CT commercial scanner designs are large and heavy. As such, this paper aims to design and develop a light-weight CT scanner for use in a mobile stroke unit (either road-based or air-based ambulance) to bring healthcare solution to patients in the rural and remote areas. We used the engineering design optimization approach to redesign and reduce the weight of the existing CT scanner with without compromised it structural performance. We managed to reduce the weight the CT scanner by three-fold while reducing design costs by allowing numerous simulations to be performed using computer software to achieve our design goals. The results are not only useful to optimize CT scanner structure to retrofit on a mobile stroke unit, but also bring the medical device solution to the market and support scalable solution to the larger community. Such an advance will allow for improved equity in healthcare whereby patients can be treated irrespective of location.**

I. INTRODUCTION

It is well-established that the diagnosis and treatment of stroke is time critical. The longer the symptoms remain untreated, the higher risk of death and disability. As such, the first hour after a stroke, what medical professionals call the 'Golden hour' is a critical time to deliver the diagnosis and treatment to a stroke patient for greater chance of surviving and avoiding long-term brain damage. In Australia, cerebrovascular disease (mainly stroke) is the third leading cause of death [1] with both ischemic (blockage of blood vessel in the brain) and hemorrhagic (leakage or rupture of a cerebral blood vessel) strokes prevalent. Although mortality from stroke has continued to decrease over the past 50 years (Figure 1A) due to improved education, detection and treatment, mortality remains high (9800/100,000 deaths in 2021) [1,2]. One reason for this, particularly in Australia, most rural communities remain unable to receive timely stroke intervention, as access to specialized stroke facilities for optimal stroke treatment are restricted to the larger cities (Figure 1B). In fact, reported treatment times for patients outside the large cities (rural hospitals) from the onset of symptoms to the admission within the hospital can take 5-30 hours and thus thrombolytic treatment of suspected stroke only occurs in less than 6% of patients (compared to 20-25% in metropolitan hospitals) [3].

In line with that seen in Germany and the United States of America, Australia has successfully launched a road based mobile stroke unit (MSU) using a standard computerized tomography (CT) scanner. The need in Australia is significant since the Australian population density is low (3 inhabitants per square kilometer) and statistics suggesting that only 3% of the acute stroke patients in rural regions can, access a stroke unit when needed [3]. The Australian road-MSU has been successful enabling 20% of patients with suspected stroke to be treated within an hour (door to clot busting treatment time reduced to 40 mins compared to 72 mins, nationally). However, the road-MSU remains limited to metropolitan Melbourne.

K. Cowell, is with the School of Engineering, RMIT University, Carlton, Melbourne, Victoria Australia (e-mail: kern.cowell@rmit.edu.au)
T. Y. Pang, is with the School of Engineering, RMIT University, Carlton, Melbourne, Victoria Australia (e-mail: tohyen.pang@rmit.edu.au)
J. S. Kwok, is with the School of Engineering, RMIT University, Carlton, Melbourne, Victoria Australia (e-mail: s3553242@student.rmit.edu.au)
C. McCrowe, is with the School of Engineering, RMIT University, Carlton, Melbourne, Victoria Australia (e-mail: chris.mccrowe@rmit.edu.au)
F. Langenberg, is with the Melbourne Brain Center, Royal Melbourne Hospital, Melbourne, Victoria, Australia (e-mail: Francesca.Langenberg@mh.org.au)
D. Easton, is with the Melbourne Brain Center, Royal Melbourne Hospital, Melbourne, Victoria, Australia (e-mail: damien.easton@thembc.org.au)
C. Williams, is with the Melbourne Brain Centre at the Royal Melbourne Hospital and the University of Melbourne, Melbourne, Victoria, Australia (e-mail: cameron.williams8@mh.org.au)
S. M. Davis, is with the Melbourne Brain Centre at the Royal Melbourne Hospital and the University of Melbourne, Melbourne, Victoria, Australia (e-mail: stephen.davis@mh.org.au)
G. A. Donnan, is with is with the Melbourne Brain Centre at the Royal Melbourne Hospital and the University of Melbourne, Melbourne, Victoria, Australia (e-mail: Geoffrey.donnan@unimelb.edu.au)
H. De Aizpurua, is with the Australian Stroke Alliance, Melbourne, Victoria, Australia (e-mail: henry.deaizpurua@austrokealliance.org.au)
A. H. Balabanski, is with is with the Melbourne Brain Centre at the Royal Melbourne Hospital and the University of Melbourne, Melbourne, Victoria, Australia (e-mail: anna.balabanski@gmail.com)
A. Dos Santos, is with the Melbourne Brain Center, Royal Melbourne Hospital, Melbourne, Victoria, Australia (e-mail: Angela.DosSantos@mh.org.au)
K. Fox is with the School of Engineering, RMIT University, Carlton, Victoria, Australia (corresponding author phone: +61-03-99254296; e-mail: kate.fox@rmit.edu.au).

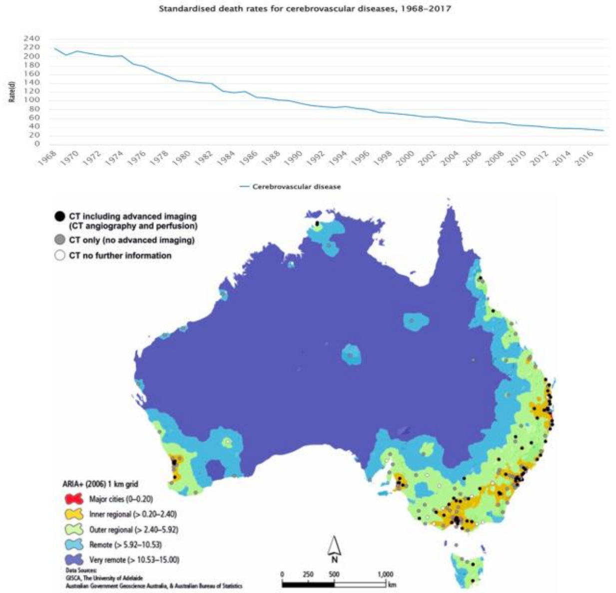

Figure 1. A: shows the death rate for cerebrovascular disease as provided by the Australian Bureau of Statistics [1] and B shows the distribution of CT scanner technologies around Australia showing a centralisation of the technologies around the capital cities. Image has been reproduced under a creative commons attribution 4.0 International license [2]

For a mobile stroke unit to meet the needs of the Australian population, the CT technology needs to change. In Australia, patient transport and emergency retrievals are undertaken by a network of road ambulances and the Australian Royal Flying Doctor Service (RFDS). Current commercial CT scanners are too large and too heavy for the conventional emergency medical service. As such, to fit medical imaging technologies into either a road ambulance or within the aeromedical fleets of Ambulance Victoria or the RFDS, the current CT scanner needs to either (i) be re-designed to provide a smaller lightweight option or (ii) a new diagnostic technology be developed. For new technologies, microwave technology as developed by EMVision and electromagnetic technologies such as that developed by MicroX are providing a pathway forward. Here however, in collaboration with the Australian Stroke Alliance and Melbourne Brain Centre, we will detail the progress of our research into the miniaturization of a CT scanner for use in road (road-MSU) or air ambulances (air-MSU).

II. EXPERIMENTAL DESIGN

Engineering design techniques were employed to modify a CT scanner (from a commercially available model) for retrofitting to a bespoke model designed for road- and air-MSU cabins. Solidworks (Dassault Systèmes, Vélizy-Villacoublay, France) was used to model both the CT scanner model and the cabin interiors. 3D Experience (Dassault Systèmes, Vélizy-Villacoublay, France) was used for topology optimization and structural analysis. To ensure that the virtual build of the CT scanner model could be completed, an analysis of the key components of a CT scanner was undertaken to establish essential componentry so that these components could be assessed for their optimal build shape, design and material. This process allowed us to substitute existing materials for lightweight alternatives and/or for re-design using design optimization techniques. As such the design process included three steps:

1. Essential component identification;
2. Essential component substitution; and
3. Essential component weight and size reduction as follows:
    a. removal of non-essential components;
    b. substitution of materials; and
    c. structural component redesign.

An example of the final model can be seen in Figure 2.

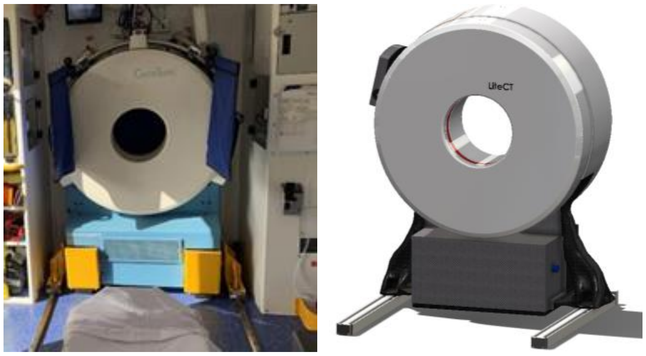

Figure 2. A: shows a commercial CT scanner (The image has been reproduced under a creative commons licence (CC BY 4.0) from [4] and B: a re-designed lightweight CT scanner

A. Virtual Models

A digital twin was first developed of the commercial CT scanner. As reported in Kwok et al [4], the digital twin provided a virtual representation of the physical CT scanner and provided a bidirectional connection of data to re-design and improve the performance of the CT scanner using computational modelling and simulations. The design process for modifying and retrofitting a CT scanner can be classified into three steps: (1) default structure reduction, (2) support structure design, and (3) integration onto a mobile stroke unit interior.

B. Structural Analysis

The heaviest component in a commercial scanner is the primary structural component, subsequently referred to as the "main frame". As the frame will need to withstand aircraft emergency landing conditions and road vehicle impact conditions, a material with high strength is required. Standards Australia's "Ambulance restraint systems" [6] states that any equipment in a road ambulance must be able to withstand accelerations of 20g (220.7 ms^{-2}) forwards and 10g (110.4 ms^{-2}) sidewards. Therefore, the main frame of the CT scanner must not fail at these accelerations. For structural finite element analysis (FEA), the main frame was fixed via the bolt holes at the bottom of the scanner to represent the fixing of the scanner to the rails and tracks, the frame was also fixed at the bolt holes connected to the arch as this is fixed to the back of the ambulance during transit. The forward load (mass of the scanner minus the linear guides, brackets, and main frame (227 kg) times the forward acceleration of 220.7 ms^{-2}) was applied at the center of mass of the scanner (Figure 3A). A separate analysis was then completed by applying the sideward load (227 kg times the sideward acceleration of 110.4 ms^{-2}) at the center of mass of the scanner (Figure 3B).

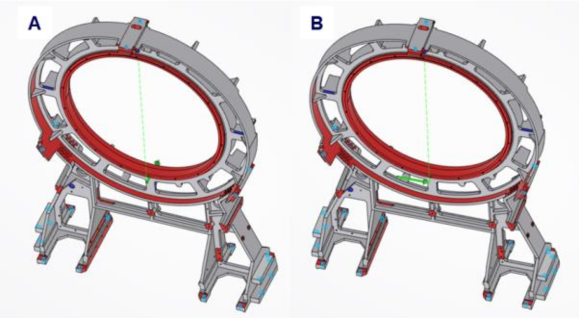

Figure 3. FEA setup of both forward (A) and sideward (B) acceleration conditions. Green arrow = load direction at centre of mass, green lines = connection from load to frame, cyan cylinders = fixed faces

III. RESULTS AND DISCUSSION

A. *Structural Analysis and Topology Optimization*

For the goal of reducing the weight of the CT scanner, high strength needs to be balanced with low density. Using Ansys Granta EduPack (ANSYS, Inc, US; 2022) materials that did not conform with the constraints for the main frame were removed. The flexural strength and density of the remaining materials were plotted using an Ashby plot and a trade-off surface drawn to identify potential materials. A carbon fiber reinforced polymer (epoxy with 55% carbon fiber) was identified as having the best strength to density ratio, however manufacturing methods such as carbon fiber forging will need to be further evaluated to ensure this large complex component can be produced using this material.

Table 1. Maximum conditions as a combination of the highest aircraft emergency landing conditions [5] and ambulance equipment crash conditions [6]. g = gravity of Earth (assumed to be 9.81 $m \cdot s^{-2}$)

Direction	Aircraft Emergency Landing Conditions (g)	Ambulance Equipment Crash Conditions (g)	Maximum conditions (g)
Upward	4g		4g
Forward	16g	20g	20g
Sideward	8g	10g	10g
Downward	20g		20g
Rearward	1.5g		1.5g

The maximum von Mises stress (value used to determine if a given material will yield or fracture) of both conditions are below the failure strength of aluminum 6061-T6 (Figure 4). Therefore, it can be postulated that during vehicle crash conditions the frame would not fail, and the CT scanner would stay fixed to its attachment points on the ambulance. To decrease the weight of this main frame for use in an aircraft, a topology optimization process was undertaken using the loads from all five directions (Table 1) with the previously determined carbon fiber material. Additionally, the attachment point at the top of the frame was removed as unlike the ambulance, a fixture to the walls of the aircraft cabin would not be possible. Figure 4C shows the final faceted main frame.

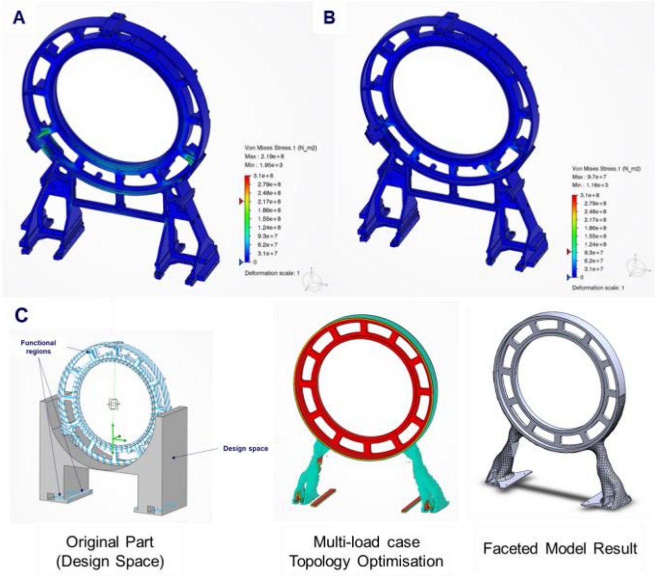

Figure 4. FEA von Mises stress results of both forward (A) and sideward (B) acceleration conditions. Scale is from 0 MPa to 3.1 x 10^8 Pa (310 MPa, Ultimate tensile strength of aluminium 6061-T6). (C) shows the topology optimisation process for the carbon fibre aircraft scanner frame.

B. *Materials for light weight scanner*

The results of the re-design and topology optimization of the CT scanner led to the development of a liteCT design. The next step was to determine both lightweight materials and components for the CT scanner. Figure 5 shows the proposed changes to the materials and components from a commercial hospital-based scanner technology to a lightweight alternative. It is noticeable that the new design uses high-end materials by swapping low-cost plastic and metal components with high-cost carbon fiber materials. This will increase the cost of the scanner however given the custom nature of the device and the low number of CT scanners to be manufactured the cost is manageable. The batteries used in commercial scanners are four lead-acid 12V batteries, which are connected in series and parallel to produce 24 V for 70 Ah. A lighter alternative to these batteries is the TB60 (True Blue Power, US) a 26 V, 60 Ah lithium-ion battery that is certified for aerospace use. To reduce weight and improve the reliability of the scanner, the centipede tracks and linear guides are to be replaced with two motorized linear actuators (MCE6071H10D0202SEF, NSK, Japan). The materials of both structural and non-structural components will be replaced with epoxy 55% carbon fiber and PEI 30% carbon fiber, respectively. To house the new batteries the lower compartment of the CT scanner was redesigned, the main frame was also redesigned for attachment with the linear actuators although structural validation of this frame is required. The total weight reduction with the removed and replaced components and the material changes is 121.9 kg, which gives a new total CT scanner weight of 240.1 kg. It is key to note that the modification of the materials and components provides a 3-fold decrease in scanner weight from a commercial hospital CT scanner (approx. 800kg).

Table 2. Substituted materials and components from commercial CT system to LiteCT system

Road-MSU CT scanner components (material)	**Weight (kg)**	**LiteCT scanner**	**Weight (kg)**
4 x WKA12-33C Batteries (lead acid)	41.76	1 x TB60 (li-ion)	24
2 x Tracks, linear rail, guides, and bracket	70.05	2 x Linear actuator	29.34
Structural components (1050, 6061-T6, steel)	87	Structural components (Epoxy 55% CF)	35.77
Non-structural components (1050, ABS)	14.1	Non-structural components (PEI 30% CF)	4.66
Gantry covers (ABS-lead)	17.56	Gantry covers (Fiber glass)	9.18

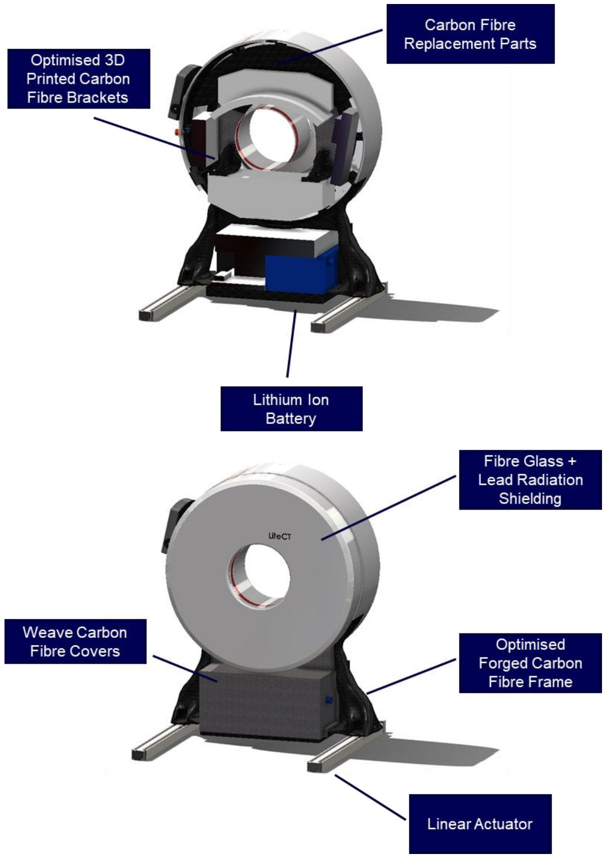

Figure 5. Key materials and components changed from commercial CT system to the LiteCT system

C. *Mobile Stroke Unit cabin fit out*

To incorporate the newly optimized main frame and to reduce the weight further, the covers and electronics tray were redesigned, and the new components added to the virtual LiteCT model. The virtual LiteCT model weighs 240.1 kg with a height of 1.33 m, width of 1.06 m and depth of 1.02 m. Figure 6 shows the new LiteCT placed inside the cabin of an AW139 helicopter. As can be seen with the addition of the standard Ambulance Victoria stretcher (Stryker MX-Pro, US) it is not possible to accommodate the full CT scanning set up as such a larger AW189 aircraft is required to fit the CT scanner and stretcher. The current road-MSU uses a modified Mercedes Sprinter 519 box van (L 3,272 mm - 4,707 mm, H 1,719 mm - 2,009 mm, W 1,555 mm) [4], however as seen in Figure 7 the LiteCT scanner in the cabin of a Mercedes Sprinter 419 (L 3,272mm - 4,307 mm, H 1,719 mm – 2,009 mm, W 1,555 mm), the standard vehicle used by Ambulance Victoria, providing an alternative solution to the 519 without the need for modifications.

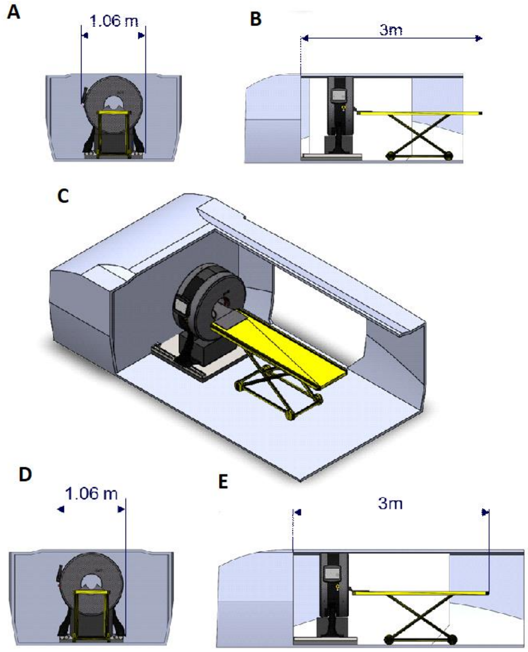

Figure 6. LiteCT virtual model and anti-vibration mounting plate and simplified Stryker stretcher inside a AW139 cabin model (A and B) showing that the scanner and stretcher will not fit instead a AW189 cabin is required isometric view (C), back view (D), side view (E)

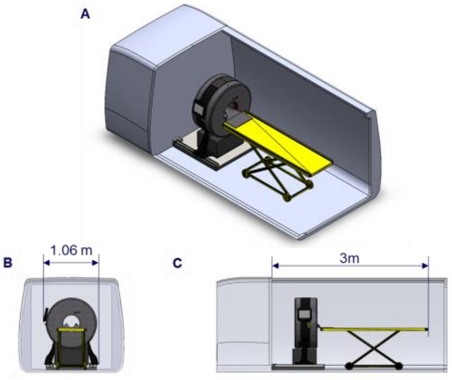

Figure 7. The LiteCT virtual model and anti-vibration mounting plate with a simplified Stryker stretcher placed within a Mercedes Sprinter 419, the standard ambulance used by Ambulance Victoria. Isometric view (A), back view (B), side view (C)

IV. CONCLUSIONS

In this manuscript we have provided a new, topology optimized design for a lightweight CT scanner. The new liteCT technology decreases the weight of a commercial CT scanner to less than 250 kg and can be retrofitted into an AW189 or the standard Mercedes Sprinter 416 ambulance cabin. The CT scanner technology may pave the way for increased capacity for our road- and air-ambulance fleets and increase the scope of mobile stroke units within Australia. Such an outcome will provide equitable access to stroke diagnostics and early intervention providing increased patient outcomes in our remote communities.

V. ACKNOWLEDGEMENTS

The authors acknowledge the resources and support of the Australian Stroke Alliance and the Melbourne Brain Centre. This research was funded by the Australian Government Department of Health Medical Research Future Fund, Frontier Health and Medical Research Grant and MTP Connect funded Australian Stroke and Heart Research Accelerator through its Targeted Translation Research Accelerator (TTRA) initiative.

REFERENCES

[1] Australian Bureau of Statistics 2021, *Causes of Death, Australia*, ABS, viewed 3 January 2023, <https://www.abs.gov.au/statistics/health/causes-death/causes-death-australia/latest-release>.

[2] Australian Bureau of Statistics 1968-2017, *Changing Patterns of Mortality in Australia*, ABS, viewed 3 January 2023, <https://www.abs.gov.au/statistics/health/causes-death/changing-patterns-mortality-australia/latest-release>.

[3] Walter S, Fassbender K, Easton D, Schwarz M, Gardiner FW, Langenberg F, Santos AD, Bil C, Fox K, Bishop L, Coote S, Zhao H, Middleton S, Bladin C, Davis SM, Donnan GA. "Stroke care equity in rural and remote areas - novel strategies". *Vessel Plus.* 2021; 5:27. http://dx.doi.org/10.20517/2574-1209.2020.102

[4] J. Kwok, K. Fox, C. Bil, F. Langenberg, A. Balabanski, A. Dos Santos, A. Bivard, F. Gardiner, C. Bladin, M. Parsons, H. Zhao, S. Coote, C. Levi, H. De Aizpurua, B. Campbell, S. Davis, G. Donnan, D. Easton and T. Pang, "Bringing CT Scanners to the Skies: Design of a CT Scanner for an Air Mobile Stroke Unit," *Appl. Sci.,* vol. 12, p. 1560, 2022.

[5] Code of Federal Regulations, United States, 1996, "Emergency Landing Conditions," *14 CFR §§ 29.561 - 29.563,*

[6] Standards Australia, 1999, "Ambulance restraint systems", *AS/NZS 4535:1999*