

Recent developments of an active ventilated vest for military use

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Abstract. Previous research has shown that an active ventilated vest can provide physiological and perceptual benefits regarding the thermal strain of a soldier. In the present article further design integration and technical developments of a ventilated vest worn in combination with Personal Protective Equipment (PPE) are described: step 1; technical improvements, step 2; improved functionality, step 3; comparison of subjective experience with commercially available passive ventilation vest during field study. To improve integration with the current ballistic system, the controller of the ventilated vest and its cables were simplified. Additionally, the new version of the ventilated vest was connected with the battery of the existing energy supply system. To improve and provide extra functionality intermittent ventilation was added. When using this intermittent ventilation, battery life was extended from ~10 to ~25 hours, while maintaining similar skin temperature compared to continuous ventilated modes, and lower skin temperature compared to a control condition ($P < 0.05$). An additional benefit of intermittent cooling was an improved cooling sensation ($P < 0.05$) compared to continuous cooling at similar fan speeds. To evaluate operational usability and perceptions for the newest version of the ventilated vest, a 5-day field study was performed during a military training in the heat (daily max. temperature: $45.2 \pm 1.2^\circ\text{C}$, daily mean relative humidity: $25.5 \pm 3.6\%$). The ventilated vest was compared to a commercially available passive ventilated vest. It was found that the active ventilated vest was perceived as more operationally usable ($P < 0.04$), more comfortable ($P < 0.001$), less warm ($P = 0.002$), and its use resulted in a higher perception of cooling ($P < 0.001$), compared to the passive vest. About 80% of the time soldiers chose full fan speed continuous ventilation during the field study. To conclude, the updated ventilated vest was subjectively evaluated as more operational usable, compared to the passive ventilated vest, especially during light intensity work, transport and breaks.

1. BACKGROUND

Military personnel are often deployed in warm and/or humid conditions. The nature of military deployment in such environmental conditions often poses high heat strain on its personnel. The combination of physical performance, personal protective clothing (PPE) [1], load carriage (together up to 50-70kg), in combination with long and unpredictable exercises [2] leads to the accumulation of this heat strain. Together, this can lead to decreased physical and cognitive performance, health illness, and in extreme circumstances even death [3].

Therefore, heat mitigation (cooling) strategies that can effectively dissipate heat produced by the soldier in these circumstances, could improve performance and decrease discomfort, while simultaneously reducing the risk of heat illness casualties. There has been research in various occupational workers and elite athletes, where mitigation strategies have proven effective in decreasing heat strain [4,5,6]. However, because of the specific demands of military deployment (e.g. electricity availability and duration of exercise) the translation of these mitigation strategies proves to be challenging.

The body's most effective method to lose heat is by evaporation of sweat [7]. However, in a military context this method may be hampered by wearing PPE [8,9]. Therefore, for soldiers wearing PPE a mitigation method specifically targeting improvement of sweat evaporation, may prove effective in decreasing heat strain. One method that could prove effective in increasing evaporation of sweat from the skin is to allow airflow between the skin and PPE, for example by forced ventilation. The principle behind this concept is explained in Figure 1. In essence the clothing and ballistic layers are by-passed, allowing evaporation of sweat from the skin and transportation to the environment. Since this forced ventilation method requires an energy source, a key advantage is its ability to function for extended durations (i.e., several hours). The ability to function for extended durations is essential in military operations, where alternative mitigation strategies, such as phase-change material vests, have a relatively limited cooling duration [6].

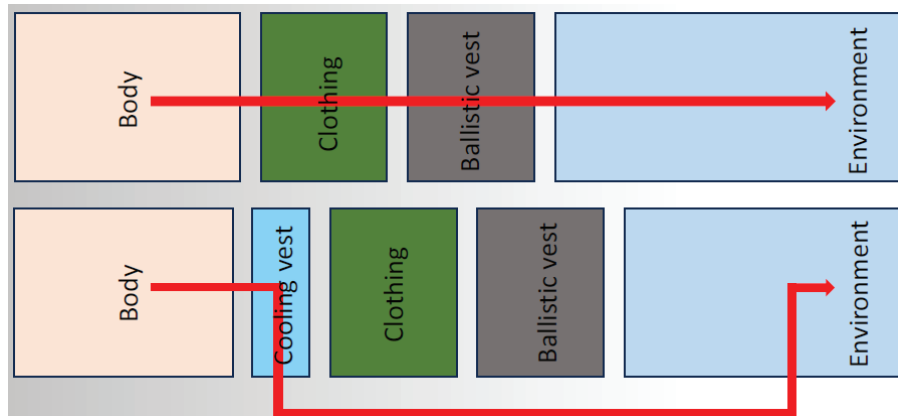


Figure 1. Schematic overview of the working principle of forcing air via the ventilated vest worn underneath the PPE system

Previous studies have published on the effectiveness of forced ventilation in decreasing heat strain in personnel wearing protective clothing [9, 10]. Glitz et al. [9] showed that wearing air-diffusing garments (in 25°C, 50% RH, performing a walking activity at 3km/h, 5% incline on a treadmill) improved performance, strain loss and thermal relief (~0.6°C lower body temperature). In addition, another cooling method 'Dry Air Comfort' (DAC), in which dry air is insufflated into the garment's microclimate, was tested previously and found effective for stationary use, because it required a flexible tube connecting personnel with an air compressor [10]. This kind of forced ventilation was also applied to helicopter pilots (unpublished data). Though this work shows that forced ventilation is effective in cooling personnel, lowering core and skin temperature, during walking exercise, in demanding thermophysiological situations, it is not a solution for a dismounted soldier due to the requirement of connection to an air compressor.

For this reason, attempts have been made to design an effective ventilated vest for the dismounted soldiers. In 2023 a ventilated vest, especially designed for the dismounted soldier of the Dutch MoD, was developed at Technology Readiness Level (TRL) 7. This was done through careful and standardized testing with a thermal manikin and climate room testing [11], however also field tests were carried out with military personnel.

The TRL 7 vest was described and illustrated in previous work from the same lab [11]. In short, the ventilation vest consists of foam parts. These parts are inserted in the front and back of an adjusted battle shirt from the Dutch MoD (Figure 2). The fabric used to adjust the battle shirt has characteristic of absorbing sweat from the skin and allowing for easy dissipation it into the air channels [11], more so than the current battle shirt. In addition, to force air through the channels four ventilators (EBMPapst, RLF35 type, St. Georgen, Hungary) were inserted in the lower area of the foam parts (Figure 2), two in the front part and two in the back part. The front and back parts are connected via electrical cables. Furthermore, in the TRL 7 iteration the foam parts were connected with two additional modules: a separate controller and an external battery. More specifications like thermal insulation and evaporation resistance were reported previously as well ([11]).



Figure 2. Illustration, description of (the inside of) the ventilation vest (previous iteration). In the left panel air inlets and outlets are shown. The right panel shows the inside of the panel with the locations of the ventilators and channels through which the air is forced, for both the front and back part. Taken with permission from [11]. Patent pending by industry partner

The present paper describes developments for further integration and optimization towards a TRL 8 of this active ventilated vest. Part of these developments are: 1) technical improvements, 2) functional improvements and 3) comparison to a commercially available ventilation vest during a field study.

2. STEPS OF DEVELOPMENT

To further develop the ventilation vest, aiming for TRL 8, prioritization of improvements were listed. Some technical issues were raised in previous field studies, mostly focusing on lessening burden for the soldier (e.g. fewer cables and improved ventilators) and the ventilated vest should be easier in use (dummy proof). This report describes both the technical and functional developments as well as the field testing conducted to reach TRL 8. Confidentiality of the (ballistic) testing facilities and about technical information prohibits communication of some of the protocol and results in full detail. If more details are warranted, contact with the corresponding author can be made.

2.1 Technical developments

2.1.1. Ballistic testing

The ventilated vest is meant to be worn underneath PPE, but it is not acceptable that the addition of the ventilated vest would decrease the functionality of PPE. Therefore, it was imperative to test the ballistic properties of the PPE in combination with ventilated vest. Ballistic testing was performed at the ballistic testing facility of TNO. The primary research question was whether wearing the ventilation vest would influence the protection and function of the PPE. With that goal in mind a series of testing was conducted using different ammunition, different PPE configuration with and without the ventilation vest, and hitting the PPE at sites where both the foam parts and the ventilator parts of ventilation vests were located. The exact protocol and results are classified, however the main results can be provided here.

The addition of the ventilated vest underneath the PPE configuration worn by the Dutch MoD resulted in a comparable or slightly increased ballistic resistance and Behind Armour Blunt Trauma (BABT) as measured with the 'V₅₀ method', when hit by different categories of ammunition. Although bullets directly aimed at the region of the ventilators are stopped, direct impact on the location of the ventilators may increase the risk of (non-lethal) secondary injury. However, the probability of this happening is considered very small. Therefore, ballistic protection remains similar (or is even slightly increased) while wearing the ventilated vest underneath the PPE configuration.

2.1.2. Hardware changes

During previous field testing military personnel provided feedback about the ventilators. Its sound was supposedly too loud (~60 dB at 3cm distance at full fan speed) and its efficiency (battery life of 6-8 hours while during full use) needed to be improved for extended use in the military context. Therefore, the ventilators type RLF35 used in the previous iteration were replaced by a new generation of the same type, which lead to a power consumption reduction of 30-40% when set at similar rotational velocity, as well as a reduction of the high-frequency sound (~10 dB at 3cm both at full and lower percentage fan speed). In addition, an extra coating was added for protection to water and salts (sweat).

In previous iterations, cables were not fully hidden, and therefore soldiers provided feedback that the cables of the ventilated vest were an annoyance or could even be a safety hazard (field study Curaçao 2023). Therefore, in the current iteration, cables were minimized as the stand-alone controller was now integrated in the cable, decreasing extra cables (see Figure 3). Also, loose cables were managed by adding appropriate holes in the fabrics.

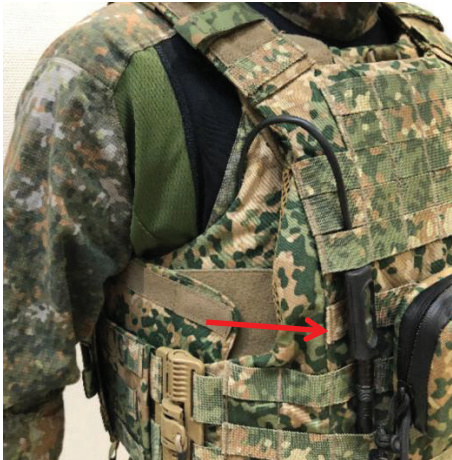


Figure 3. Picture of the ventilated vest worn underneath the PPE system. In this picture it can be seen that loose hanging cables are minimized. The arrow points towards the new controller, incorporated in the cable connecting the battery

As mentioned above, another technical development was the integration of the controller in the cable. In previous iterations of the ventilated vest a stand-alone controller was part of the system. However, after feedback on the complexity of the system and the wish for dummy proof use, this new model was introduced. In addition, the controller was directly linked to the battery (Figure 3).

A development which was very important for the Dutch MoD was the integrating of the ventilated vest with the battery of the PPE system used by the MoD (Bren-Tronics, Li-ION battery). The realization of this development improved the functionality of the ventilated vest in multiple ways. As no external battery was needed anymore, it simplified the system. Additionally, by using the MoD's own power source it is anticipated that logistical problems are less likely to occur. A possible disadvantage is that the PPE-battery is used for more purposes and may therefore run out of energy earlier. This may increase the need for battery life management. This issue was addressed by performing tests on power usage of the ventilated vest. Depending on the condition used the battery life of the ventilated vest was between 11 hours (full fan speed) to 64 hours (40% of fan speed). The need to use the ventilated vest on full fan speed is only during specific moments, e.g. highly physical activities, therefore it is anticipated that the current battery life using the ventilated vest is sufficient for operational use. This however, remains to be confirmed.

2.2 Functional developments

One of the most important goals was to improve the operational useability of the ventilated vest. Therefore, it was important to improve battery life (as described above), but also to reduce (subjective) heat strain, to increase acceptance of the system by military personnel. Physiological effectiveness of the ventilated vest was shown previously by reducing core and skin temperature by -0.3 ± 0.2 °C and -1.1 ± 1.3 °C in 32 °C and 33 % relative humidity, 5 km/h walking speed [11]. Additionally, a climate room study (Soesterberg, The Netherlands) was performed to test the effect of the cooling method (thermal alliesthesia, i.e., change of perception depending on the body's thermal state) on cooling sensation and skin temperature of the ventilation vest [12]. The different cooling conditions used in that study were 70% and 100% continuous fan speed and 70% intermittent fan speed (alternating fan speed during cycles of 30 sec).

From that study it was concluded that the ventilated vest caused a reduction in subjective thermal strain. More specifically, the intermittent condition seemed to have an additional benefit on cooling sensation (the sense of cooling, which is scored from none to extremely high), compared to the other two continuous ventilated conditions. For thermal sensation (which is scored from cold to hot), the additional benefit of intermittent was not observed. Additionally, while the intermittent version used less power (18 hours vs. 11 hours at full fan speed, data not shown) and blew less air through the vests, it still resulted in similar scapula skin temperature under the vest as the other two ventilated vest conditions, which was lower than the control conditions. Therefore, for the further development of the ventilated vest towards TRL 8, it was concluded that the intermittent functionality was beneficial concerning reducing subjective thermal strain.

2.2 Comparison to a commercially available product

A field study was conducted in Senegal, Africa. The main objective of this field study was to test and assess the operational usability of the ventilation vest during semi-controlled military conditions. In addition, a second aim was to compare its functionality with a commercially available passive ventilation system. Claims of that passive vest regarding cooling were similar or even better than the results of the recently developed active ventilation vest [11]. Therefore, it was of interest to compare the two ventilation vests on subjective cooling, thermal comfort and sensation (Figure 4).



Figure 4. Example of active ventilated vest worn (A) and stand-alone (B) and the passive commercially available product on the inside of the ballistic configuration (C)

The protocol was approved by the local ethical committee of TNO (2024-040). To this end 15 male subjects of the regiment were included (43rd Mechanized Brigade). Due to practical issues outside of the researchers control a total of 24 observations were completed (13 with the active ventilated vest and 11 with the commercially available product) over 4 days. An additional group of 15 subjects of the regiment was included as a control group, This group did not wear the ventilation vests, only PPE, during identical exercises.

At the end of each day the passive and active ventilation vests were distributed among the subjects. Additionally, the configuration and set-up of both the ventilation vests and PPE were visually checked. At the end of the testing day subjects filled in a questionnaire which consisted of 27 questions, evaluating specific parts of functionalities, thermal comfort scored from 0 (comfortable) to 4 (extremely uncomfortable) (ISO10551, 2001), thermal sensation scored from -3 (cold) to +3 (hot) (ISO10551, 2001), cooling sensation scored from 0 (none) to 6 (extremely high) (TNO), and overall rating of functionality/usability scored from 1 (extremely bad) to 7 (extremely good) [13].

Training sessions performed during the measurement period were a speed march, static shooting, and active shooting, ranging from 1.5 to 4.5 hours. The maximum air temperature during the measuring period was between 43.6-47.0 °C, relative humidity ranged between 22-31.8%, and average UV index was 9.7.

Thermal sensation was significantly lower ($P < 0.05$) in the (active) ventilation vest (1.9 ± 0.6), compared to the commercially available vest (2.8 ± 0.4 , Figure 5A). In addition, the control group, only wearing PPE, was asked the same questions, during the same training. The thermal sensation of the active ventilation group was also significantly lowered compared to the thermal sensation scored by the control group (2.6 ± 0.4 , $P < 0.05$). In addition, also the thermal comfort (Figure 5B) and cooling sensation (Figure 5C) were significantly improved by the ventilation vest (1.0 ± 0.4 and 3.5 ± 0.7) compared to the commercially available product (2.4 ± 1.1 and 0.8 ± 0.9 , $P < 0.05$).

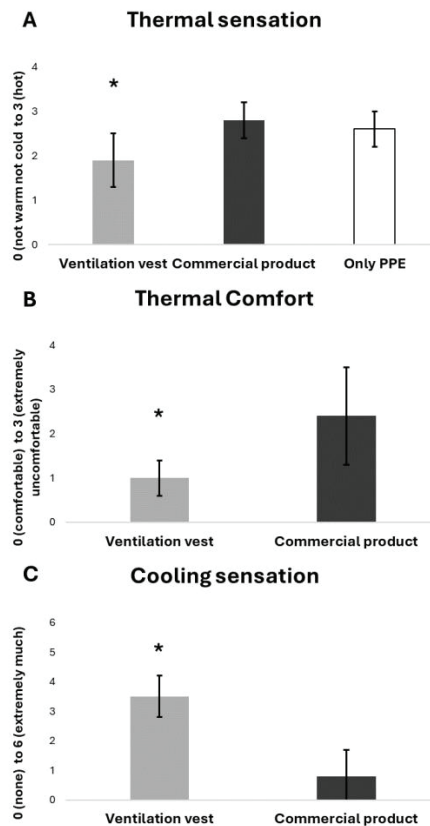


Figure 5. Thermal sensation (A) for the ventilation vest compared to the commercially available product and a control group wearing only PPE (* = $P < 0.05$). Also (B) thermal comfort and (C) cooling sensation were significantly improved by the ventilation vest compared to the commercially available product (* = $P < 0.05$)

Additionally, while wearing the ventilation vest, the evaluation on ‘usability of vests for military tasks’, was also significantly improved, compared to the commercially available product (Figure 6, * = $P < 0.05$).

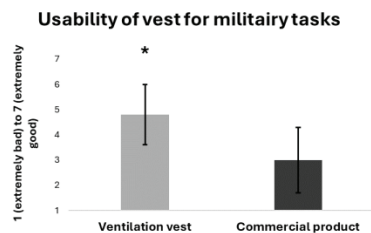


Figure 6. Usability of the vests was evaluated. The (active) ventilation vest was scored significantly higher than the commercially available product (* = $P < 0.05$)

During the training the subjects were free to use the active ventilated vests in the modality they preferred (continuously or intermittent, full fan speed - 100% - or a lower percentage). Interestingly, during about 80% of the observations the subjects used the continuous, full fan speed setting of the active ventilation vest. This possibly means that there is a difference between cooling sensation (see intermittent developments) and the overall preference of the modality. Therefore, more evaluations specifically on the perception of the different ventilation vest modalities in the field is recommended for the near future.

Since the training was performed in low relative humidity levels (22.0-31.8%), the subjects were informed about the possibility of ‘pre-wetting’ the vests, to support the natural wetting of the fabrics by

sweat. This was done a lot (though not systematically noted) with both vests by the subjects. Especially in the active ventilated vests this was perceived as an immediate cooling or relief.

Therefore, it can be concluded that the ventilated vest improved thermal sensation over wearing PPE only in the field and was scored useful by the subjects. In addition, on thermal sensation, comfort and cooling sensation the (active) ventilated vest scored significantly better than the commercially available product, which works on passive ventilation. Hence, the developed active ventilated vest provide a (subjective) advantage during operational use in the heat.

3. FUTURE DEVELOPMENTS AND CONCLUSION

This project was designed to produce a functional and usable cooling solution for the dismounted soldier wearing PPE. In addition to previous work [14, 15], the specific goal for this project was to better integrate the system with the PPE system used by the Dutch MoD and to test it in a realistic setting.

Hence, with both technical and functional updates of the active ventilated vest abovementioned goal was met. This cooling solution is not meant to cool aggressive and quickly for a short time, but moderate for a long period needed for operational use (>8 hours). Results from climate room testing and field tests, support this.

The product is effective in cooling military personnel during operational use in the heat (measured both physiologically as well as subjectively) and its ballistic protection is at least comparable to wearing only PPE. In addition, technical improvements have made the ventilation vest less complex and more integrated in the PPE system currently used by the Dutch MoD. The product was also evaluated during field testing (both in Curaçao and Senegal), and assessed as usable by the subjects. In addition, the technical and functional improvements of the current iteration have led to a product at a TRL 8. Obviously small improvements can still be made (e.g. positioning of cables and interaction with shooting position of gun). Other developments foreseen for the near future include creating suitable and usable cooling solutions, using the same technology, for other parts of the MoD.

In conclusion, the developments and positive evaluation of the active ventilated vest have demonstrated its effectiveness in reducing heat strain for dismounted soldiers wearing PPE in warm conditions.

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