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Simulation and education

Evaluation of functional and electrical features of automatic external defibrillators in extreme altitude and temperature environments

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Abstract

Aims: Human exposure to high-altitude and/or low-temperature areas is increasing and cardiac arrest in these circumstances represents an increasing proportion of all treated cardiac arrests. However, little is known about the performance of automated external defibrillators (AED) in these circumstances. The objective of this study is to assess the functional and electrical features of 6 commercially available AEDs in extreme environments.

Methods: Accuracy of shockable rhythm detection, the time required for self-test, rhythm analysis, and capacitor charging, together with total energy, peak voltage, peak current, and phasic duration of defibrillation waveform measured after placing the AEDs in simulated high-altitude, simulated low-temperature, and natural composite high-altitude and low-temperature environment for 30 min, were compared to those measured in the standard environment.

Results: All of the shockable rhythms were correctly detected and all of the defibrillation shocks were successfully delivered by the AEDs. However, the time required for self-test, rhythm detection, and capacitor charging was shortened by 1.2% (3 AEDs, maximum 12.4%) in the simulated high-altitude environment, was prolonged by 3.6% (4 AEDs, maximum 40.8%) in the simulated low-temperature environment, and was prolonged by 4.1% (5 AEDs, maximum 52.1%) in the natural environment. Additionally, the total delivered energy was decreased by 2.5% (2 AEDs, maximum 6.8%) in the natural environment.

Conclusion: All of the investigated AEDs functioned properly in simulated and natural environments, but a large variation in the functional and electrical feature change was observed. When performing cardiopulmonary resuscitation in extreme environments, the impact of environmental factors may need consideration.

Keywords: Cardiac arrest, Ventricular fibrillation, Automated external defibrillator, High altitude, Low temperature, Extreme environments

Introduction

High-altitude regions account for approximately 27% of the earth's surface and human exposure to these regions is increasing. It is estimated that 40 million inhabitants live permanently above 3000 m, with an additional 100 million tourists traveling to these areas each year.[1] As altitude increases, the decrease in oxygen supply may cause several acute and chronic physiological changes, and lead to serious cardiovascular or cardiopulmonary events.[2] In addition to hypoxia, high-altitude environments are also accompanied by low temperatures. For every 1000 m ascent in altitude, the ambient temperature decreases by approximately 5.5 °C. This harsh natural environment will further increase the risk of death, especially for men after age 40 with cardiac disease.[3,4] Although the incidence of cardiac arrest (CA) in extreme altitude and temperature environments remains unclear, there is evidence that CA is the second most common cause of death in high-altitude areas and represents an increasing proportion of all treated CAs.[2,5–7]

Ventricular fibrillation (VF) is the most common initial rhythm for CA of cardiac origin.[8] High-quality cardiopulmonary resuscitation (CPR) and early defibrillation are the most important determinants of survival for victims of VF.[9] The automated external defibrillator (AED) is developed to meet the need for fast access in public places

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and used by lay responders.[10] In recent years, more and more evidence supports the association between bystander use of AED and improved outcomes, with a probability of surviving an out-of-hospital CA of more than 50% in patients with shockable rhythms.[11–13]

With the rapid and widespread diffusion of AEDs, the possibility of using an AED in special circumstances is also increasing. The available data suggests that AEDs can be safely used in wet environments, in rigid inflatable boats, in aircraft environments, and in moving ambulance vehicles.[11,14–17] However, little is known about the performance of AEDs in extreme altitude and temperature environments. The current study was designed to systematically assess the functional and electrical features of several commercially available AEDs in high-altitude and/or low-temperature environments.

Methods

The study was approved by the Medical Ethics Committee of the Army Medical University (2020-002-02). The experiments were conducted between December 2021 and February 2022. The study was following the Chinese Calibration Specification for Cardiac Defibrillators (JJF 1149-2014).

Device description

Six commercially available AEDs sold in China from different manufacturers were selected for the study. The device model and operating condition specified in the technical manuals are listed in Table 1. The environmental specifications of different types of AEDs have good consistency, with the lower limit of altitude of −381 to 0 m, the upper limit of altitude of 4000 to 4575 m, the lower limit of temperature of −5 to 0 °C, the upper limit of temperature of 40 to 50 °C, the lower limit of humidity of 0 to 30%, and the upper limit of humidity of 95%.

A defibrillator analyzer and pacemaker tester (Impulse 7000D, Fluke Biomedical, Cleveland, OH, USA) were used to output ECG waveforms used by AEDs for rhythm analysis and to measure the defibrillatory parameters when a shock is delivered. A total of 3 non-shockable rhythms (normal sinus rhythm, atrial fibrillation, and asystole) and 3 shockable rhythms (coarse VF, fine VF, and ventricular tachycardia) were simulated by the analyzer. The operating condition specified in the technical manual of the analyzer is the temperature between 10 and 40 °C, and the humidity between 10 and 90%.

An impedance simulator (Impulse 7010, Fluke Biomedical, Cleveland, OH, USA) was used to simulate the AED's load of low, medium, and high impedance (50 Ω, 100 Ω, and 150 Ω).

Extreme environment simulation and field selection

A total of 8 different environments labeled as E1 to E8 (Fig. 1) were used to assess the functionality of the AEDs.

Standard environment E1: A medical instrument testing laboratory located in Chongqing, with the temperature of 22 ± 2 °C, the altitude of 330 m, and the humidity of 40.2 ± 2.6%. This environment was also used as the reference for comparing the testing results in other environments.

Simulated high-altitude and normal temperature environments E2-E4: A human-rated altitude chamber (DYC-2842 T, Halei Aerospace Environmental Engineering Co., Ltd, Anshun, Guizhou, China) with the altitude set to 3000 m, 4000 m, and 5000 m, the temperature of 22 ± 2 °C and the humidity of 40.9 ± 3.7%.

Simulated low-temperature and normal altitude environment E5-E7: A human-rated temperature chamber (HLTH3-35, Halei Aerospace Environmental Engineering Co., Ltd, Anshun, Guizhou, China) with the temperature set to 0 °C, −15 °C and −25 °C, the altitude of 330 m and the humidity of 73.2 ± 3.2%.

Natural composite high-altitude and low-temperature environment E8: An outdoor field environment at the altitude of 4516 m, with the temperature between −15 °C and −20 °C, and the humidity of 88.7 ± 6.1% located in Naqu, Tibet.

Experimental procedures

All tests were made by a medical doctor and a biomedical engineer. All devices were placed in the experimental environment for 30 min before testing. During the experiment, the doctor operated the AEDs, while the engineer operated the analyzer in the other room. The engineer operating the analyzer was not aware of the order of the AED being tested, and they communicated with each other through two wireless walkie-talkies.

Because the defibrillator analyzer did not provide altitude parameters for operation, the impact of altitude on its performance was investigated before the experiment. First, two randomly selected AEDs were tested with both the AED and analyzer placed in environment E1. Second, the AEDs were repeatedly tested with the analyzer placed at environments E2, E3, and E4 respectively.

The flowchart of the experiment is shown in Fig. 1. First, the AEDs were tested in a randomized order with both the AED and analyzer placed in E1. After connecting with the AED and with the

Table 1 – Device model and operating condition specified in the technical manual of the investigated automated external defibrillators.

Device Model	Manufacture	Temperature	Altitude	Humidity
LIFEPAK CR Plus	Physio-Control, Redmond, WA, USA	0 °C ~ 50 °C	0 m ~ 4572 m	5% ~ 95%
HSI	Philips, Seattle, WA, USA	0 °C ~ 50 °C	0 m ~ 4572 m	0% ~ 95%
AED7000	M&B, Beijing, China	0 °C ~ 40 °C	−91 m ~ 4573 m	30% ~ 95%
Bene Heart D1	Mindray, Shenzhen, Guangdong, China	−5 °C ~ 50 °C	−381 m ~ 4575 m	5% ~ 95%
AED Pro	ZOLL, Chelmsford, MA, USA	0 °C ~ 50 °C	−91 m ~ 4573 m	10% ~ 95%
Amoul I3	AMBULANC, Shenzhen, Guangdong, China	0 °C ~ 40 °C	0 m ~ 4000 m	15% ~ 95%

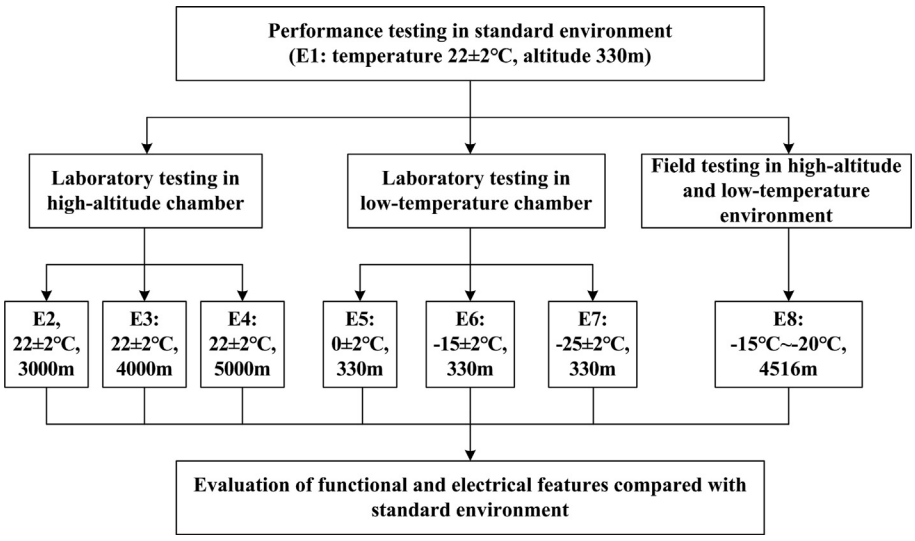

Fig. 1 – Flowchart of the experiment.

impedance simulator, the analyzer was set to defibrillation analysis mode and output the waveform with a specific cardiac rhythm. The power of the AED was then turned on. After self-test, rhythm analysis, and capacitor charging (only for shockable rhythms), the discharge button of the AED was pressed according to the voice prompt. The AED was turned off when the defibrillation parameters were reported by the analyzer. For each AED, this process was repeated until all of the six rhythms and three load impedances were tested. Second, the AEDs were tested in a randomized order in the high-altitude chamber (E2, E3, and E4) with the analyzer remaining placed in E1. Third, the AEDs were tested in a randomized order in the low-temperature chamber (E5, E6, and E7) with the analyzer remaining placed in E1. Fourth, the AEDs were tested in a randomized order in E8, with the analyzer placed in a nearby room of normal temperature.

Functional and electrical features measurement

The analysis results prompted by the AEDs, together with the defibrillation parameters reported by the analyzer were recorded by the investigators.

Accuracy for rhythm detection was determined by the total number of correctly classified rhythms divided by the total number of tested rhythms in each environment. Since the voice prompts and time required for self-test, rhythm analysis and capacitor charging were different in each AED, two functional features named $T_{nonshock}$ and T_{shock} were measured for comparison. $T_{nonshock}$ was the period recorded from the AED power on to the prompt of "no shock advised", it represents the total time required for self-test and rhythm analysis. T_{shock} was the period recorded from the AED power on to the prompt of "press the shock button", it represents the total time required for self-test, rhythm analysis, and capacitor charging.

Five electrical features, including total delivered energy (E), peak voltage (V_p), peak current (I_p), phase 1 duration (T_1), and phase 2 duration (T_2) were measured in each shock.

Statistical analysis

Continuous variables are presented as mean ± standard deviation and compared using one-way ANOVA analysis. Categorical variables are presented as percentages and compared with Fisher's exact test. Statistical analyses were done in SPSS version 22 (IBM Corp, Armonk, NY, USA), and a p value < 0.05 was considered statistically significant.

Results

All of the devices functioned properly, i.e. they could perform self-test, rhythm analysis, charging, and discharging functions in all of the 8 environments. All of the shockable rhythms were successfully identified and the accuracies for rhythm detection were 100% for each AED. A total of 72 shocks were delivered by each AED according to the voice prompt and all of the defibrillation parameters were successfully recorded.

Testing results in standard environments

The functional and electrical features of the AEDs in E1 are shown in Table 2. A large variation in these features was observed, with the $T_{nonshock}$ between 12.3 to 20.1 s, T_{shock} between 17.2 to 23.8 s, E between 131 to 200 J, V_p between 952 to 1776 V, I_p between 11.6 and 21.4A, T_1 between 6.0 to 16.2 ms, and T_2 between 4.0 to 8.4 ms. It is worth noting that T_{shock} was longer than $T_{nonshock}$ in 4 AEDs but identical in the other 2 AEDs. Additionally, both T_1 and T_2 were prolonged as the impedance increased in 4 AEDs except one kept constant.

Impacts of high-altitude on the performance of defibrillator analyzer

AED Pro and Amoul I3 were chosen to test the impact of altitude on the performance of the defibrillator analyzer. The testing results are shown in Table 3 and the features measured in three different altitudes were similar to those measured in E1.

Impacts of high-altitude on the functional and electrical features of AEDs

The testing results of placing the AEDs in E2 ~ E4 and placing the analyzer in E1 are shown in Fig. 2 and Table 4. Compared with E1, the relative variation ranged from −12.41% to 2.07% and with an average of −1.21 ± 3.25%. Significant differences in the functional features were observed in 4 AEDs.

Table 2 – Functional and electrical features of the investigated automated external defibrillators in the standard environment.

	Device					
Feature	LIFEPAK CR Plus	HSI	AED7000	Bene Heart D1	AED Pro	Amoul I3
$T_{nonshock}$ (s)	12.3 ± 0.4	17.3 ± 0.2	14.2 ± 0.1	20.0 ± 0.1	20.1 ± 0.2	13.3 ± 0.2
T_{shock} (s)	20.1 ± 0.7	17.2 ± 0.1	21.2 ± 0.4	20.3 ± 0.3	23.8 ± 0.1	20.6 ± 0.7
E (J)	200.3 ± 0.6	151.5 ± 3.4	146.2 ± 4.3	181.6 ± 12.5	130.5 ± 9.5	157.6 ± 5.3
Vp (V)	1550 ± 111	1722 ± 94	952 ± 13	1457 ± 55	1311 ± 275	1776 ± 62
Ip (A)	18.4 ± 7.7	20.6 ± 9	11.6 ± 5.6	17.6 ± 7.9	14.6 ± 3.8	21.4 ± 9.8
T_1 (ms)	9.3 ± 1.6	7.9 ± 2.9	16.2 ± 6.0	10.1 ± 1.8	6.0 ± 0.0	8.0 ± 2.9
T_2 (ms)	6.2 ± 1.1	5.8 ± 1.3	8.4 ± 3.0	6.2 ± 0.9	4.0 ± 0.0	5.7 ± 1.4

Table 3 – Effects of altitude on the performance of defibrillator analyzer.

Device	Feature	E1	E2	E3	E4
AED Pro	$T_{nonshock}$ (s)	20.1 ± 0.2	20.0 ± 0.2	20.0 ± 0.3	20.1 ± 0.3
	T_{shock} (s)	23.3 ± 0.5	23.3 ± 0.4	23.4 ± 0.4	23.4 ± 1.3
	E (J)	129.5 ± 9.8	129.4 ± 9.9	129.2 ± 10.0	129.5 ± 9.6
	Vp (V)	1305 ± 280	1305 ± 280	1303 ± 281	1306 ± 277
	Ip (A)	14.5 ± 3.7	14.5 ± 3.7	14.5 ± 3.7	14.5 ± 3.7
	T_1 (ms)	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0
	T_2 (ms)	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0
Amoul I3	$T_{nonshock}$ (s)	13.2 ± 0.3	13.0 ± 0.3	13.01 ± 0.45	13.3 ± 0.4
	T_{shock} (s)	20.8 ± 0.5	20.2 ± 1.1	20.5 ± 0.6	21.02 ± 0.9
	E (J)	155.4 ± 5.9	155.1 ± 6.2	155.4 ± 5.8	155.3 ± 5.9
	Vp (V)	1755 ± 68	1748 ± 74	1750 ± 75	1748 ± 74
	Ip (A)	21.1 ± 9.4	21.0 ± 9.4	21.0 ± 9.4	21.0 ± 9.4
	T_1 (ms)	8.0 ± 2.9	8.0 ± 2.9	8.0 ± 2.9	8.0 ± 2.9
	T_2 (ms)	5.7 ± 1.4	5.8 ± 1.3	5.8 ± 1.3	5.8 ± 1.3

Impacts of low-temperature on the functional and electrical features of AEDs

The testing results of placing the AEDs in E5 ∼ E7 and placing the analyzer in E1 are shown in Fig. 2 and Table 4. Compared with E1, the relative variation ranged from −7.62% to 40.76% and with an average of 3.60 ± 8.23%. Significant differences in the functional and electrical features were observed in 5 AEDs.

Impacts of composite high-altitude and low-temperature environment on the functional and electrical features of AEDs

The testing results of placing the AEDs in E8 and placing the analyzer in the high-altitude environment with normal temperature (4516 m, 17 °C) are shown in Fig. 2 and Table 4. Compared with E1, the relative variation ranged from −6.77% to 52.10% and with an average of 4.09 ± 13.79%. Significant differences in the functional and electrical features were observed in 5 AEDs.

Discussion

Early defibrillation and high-quality CPR with minimal interruption of chest compressions are the most important interventions in normal environments.[6] However, as CA and CPR after ascent to high altitude have not been extensively studied, it remains unknown whether resuscitation protocols are as effective as at sea level or if they should be adapted to the relevant physiological derangements.[7]

CA at high altitudes represents a unique, difficult, and complex situation and there is an imperative need for further research to obtain a favorable outcome. In high altitudes, humans are exposed to an environment of hypoxia. Hypoxia and other associated environmental conditions, such as low temperature, thermal stress, dehydration, and unusual physical exertion may affect the physiological and pathological process of CA and CPR.[4,6] Therefore, the uncertainty will be greatly increased when standard CPR is performed in these extreme environments. First, the reduced O_2 supply and paradoxical vasoconstriction can have a potential impact on the effect of CPR.[7,18] Second, CPR at high altitudes exerts a significant physical effect and leads to a rapid decline in the quality of CPR.[19–22] Third, high-altitude areas have limited AED accessibility and fewer medical resources.[23] Treatments for CA of cardiac origin are time sensitive and the resuscitation effort is most effective only when the victims have received immediate CPR with an AED.[24,25]

Although the placement of AEDs and the establishment of the chain of survival are crucial for achieving favorable outcomes, just establishing these infrastructure facilities is not enough. On the one hand, the availability of an AED needs to be considered due to the low utilization rate of the device.[26] On the other hand, the usability of an AED also needs to be considered, especially at the scene of out-of-hospital CA for bystanders.[27] The failure and/or delay

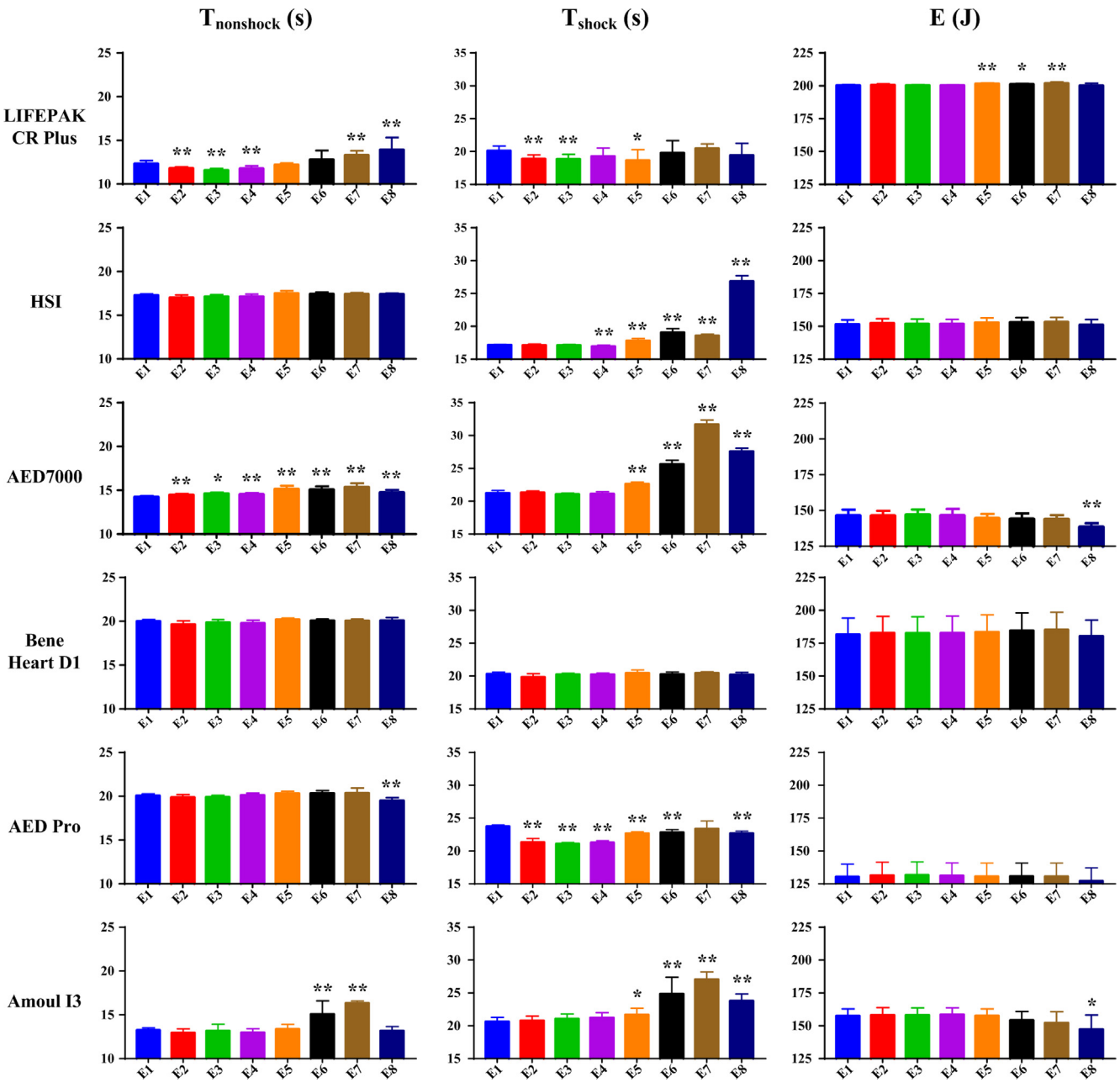

Fig. 2 – Time period from the AED power on to the prompt of "no shock advised" ($T_{nonshock}$), time period from the AED power on to the prompt of "press the shock button" (T_{shock}), and total delivered energy (E) of the investigated automated external defibrillators (AEDs) at different environments. *: $p < 0.05$ compared with E1, **: $p < 0.01$ compared with E1.

in shock delivery might be attributed to poor design and lack of usability of AEDs.[27,28]

Considering that more and more scenarios of CAs exceed the range of AED operating environments, we tested the functionality and performance of AEDs in simulated and natural extreme environments. Among the 6 AEDs that were investigated, significant changes in the functional and electrical features were observed in 5 AEDs. More specifically, 3 AEDs were affected by the high-altitude environment, 5 AEDs were affected by the low-temperature environment, and 5 AEDs were affected by the composite high-altitude and low-temperature environment. Among the 3 features that were markedly affected by the operating environment, all of them declined in 1 AED while both declining and rising were observed in 4 AEDs. More importantly, low temperature had a significant impact on the functional features and prolonged the time required for self-test, rhythm analysis, and capacitor charging by an average of 3.6% (with a maximum rise of 40.8%). In contrast, high altitude had a relatively small impact on performance and declined this time by an average of 1.2% (with a maximum decline of 12.4%). The composite high-altitude and low-temperature environment affected the features mainly by the low temperature. In addition to prolonging this time by an average of 4.1% (with a maximum rise

Table 4 – Peak voltage, peak current, first and second phase duration of the investigated automated external defibrillators in different environments.

Device	Feature	E1	E2	E3	E4	E5	E6	E7	E8
LIFEPAK CR Plus	Vp (V)	1550 ± 111	1550 ± 111	1548 ± 111	1549 ± 110	1552 ± 113	1550 ± 111	1552 ± 108	1538 ± 121
	Ip (A)	18.4 ± 7.7	18.4 ± 7.8	18.4 ± 7.8	18.4 ± 7.8	18.4 ± 7.7	18.4 ± 7.7	18.5 ± 7.8	18.2 ± 7.5
	T_1 (ms)	9.3 ± 1.6	9.3 ± 1.6	9.3 ± 1.6	9.3 ± 1.6	9.3 ± 1.6	9.3 ± 1.6	9.3 ± 1.6	9.3 ± 1.6
	T2 (ms)	6.2 ± 1.1	6.2 ± 1.1	6.2 ± 1.1	6.2 ± 1.1	6.2 ± 1.1	6.2 ± 1.1	6.2 ± 1.1	6.3 ± 1
HSI	Vp (V)	1722 ± 94	1715 ± 95	1713 ± 95	1714 ± 95	1728 ± 96	1728 ± 95	1730 ± 98	1703 ± 101
	Ip (A)	20.6 ± 9	20.5 ± 8.9	20.5 ± 8.9	20.5 ± 8.9	20.6 ± 9	20.7 ± 9	20.7 ± 9	20.3 ± 8.8
	T_1 (ms)	7.9 ± 2.9	7.9 ± 2.9	7.9 ± 2.9	8.0 ± 2.9	8.0 ± 2.9	8.0 ± 2.9	7.9 ± 2.9	8.0 ± 3.0
	T_2 (ms)	5.8 ± 1.3	5.8 ± 1.3	5.8 ± 1.3	5.8 ± 1.3	5.8 ± 1.3	5.8 ± 1.3	5.8 ± 1.3	5.9 ± 1.4
AED7000	Vp (V)	952 ± 13	953 ± 15	954 ± 13	951 ± 17	954 ± 18	955 ± 15	958 ± 17	934 ± 27
	Ip (A)	11.6 ± 5.6	11.6 ± 5.5	11.6 ± 5.6	11.6 ± 5.5	11.6 ± 5.5	11.6 ± 5.5	11.7 ± 5.5	11.3 ± 5.3
	T_1 (ms)	16.2 ± 6	16.2 ± 6.2	16.2 ± 6.2	16.1 ± 6.2	16 ± 6.2	15.7 ± 6.1	15.7 ± 6.1	15.7 ± 6
	T_2 (ms)	8.4 ± 3	8.3 ± 2.9	8.4 ± 2.9	8.5 ± 2.8	8.3 ± 2.8	8.4 ± 2.8	8.3 ± 2.9	8.5 ± 2.9
Bene Heart D1	Vp (V)	1457 ± 55	1461 ± 56	1461 ± 57	1461 ± 56	1463 ± 54	1468 ± 52	1471 ± 52	1444 ± 58
	Ip (A)	17.6 ± 7.9	17.6 ± 8	17.6 ± 8	17.6 ± 8	17.7 ± 8	17.7 ± 8.1	17.7 ± 8.1	17.4 ± 7.8
	T_1 (ms)	10.1 ± 1.8	10.1 ± 1.8	10.1 ± 1.8	10.1 ± 1.8	10.1 ± 1.8	10.1 ± 1.8	10.1 ± 1.8	10.2 ± 1.8
	T_2 (ms)	6.2 ± 0.9	6.2 ± 0.9	6.2 ± 0.9	6.2 ± 0.9	6.3 ± 0.9	6.3 ± 0.9	6.3 ± 0.9	6.3 ± 0.9
AED Pro	Vp (V)	1311 ± 275	1316 ± 280	1318 ± 281	1316 ± 281	1310 ± 280	1309 ± 279	1307 ± 278	1286 ± 276
	Ip (A)	14.6 ± 3.8	14.6 ± 3.8	14.6 ± 3.8	14.6 ± 3.7	14.6 ± 3.7	14.6 ± 3.7	14.5 ± 3.7	14.3 ± 3.6
	T_1 (ms)	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0	6.0 ± 0.0
	T_2 (ms)	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0	4.0 ± 0.0
Amoul I3	Vp (V)	1776 ± 62	1774 ± 69	1775 ± 67	1778 ± 65	1773 ± 65	1751 ± 70	1739 ± 80	1695 ± 100
	Ip (A)	21.4 ± 9.8	21.4 ± 9.7	21.4 ± 9.7	21.4 ± 9.8	21.4 ± 9.7	21.1 ± 9.5	20.9 ± 9.3	20.2 ± 8.8
	T_1 (ms)	8.0 ± 2.9	7.9 ± 2.9	7.9 ± 2.9	7.9 ± 2.9	8.0 ± 2.9	8.0 ± 3.0	8.0 ± 3.0	8.2 ± 2.9
	T_2 (ms)	5.7 ± 1.4	5.7 ± 1.3	5.7 ± 1.4	5.7 ± 1.3	5.7 ± 1.4	5.7 ± 1.4	5.8 ± 1.4	5.8 ± 1.4

of 52.1%), it also declined the delivered energy by 2.5% (with a maximum decline of 6.8%).

This is the first study to investigate the impact of harsh operating environments on the functional and electrical features of AEDs. The difference in the adaptability to extreme environments is mainly due to the discrepancy in circuit design and electronic components adoption. AED consists of signal detection and analysis unit, electronic control unit, high-voltage charging and discharging unit, electrodes, and battery. Low-temperature environments can cause changes in the parameters of the key components, including resistors, capacitors, transistors, and batteries, thereby affecting the functionality, performance, and reliability of medical devices. When these components are placed in a high-altitude environment, their heat dissipation performance, insulation performance, and sealing performance will be affected, which may also affect the working performance of medical devices.[29,30]

The findings that the environmental adaptability of AEDs is different are of great significance for CPR and defibrillation in special circumstances. On the one hand, the length of the pre-shock hands-off pause is a key variable that determines the defibrillation outcomes.[31] Prolonging the time required for self-test, rhythm analysis and capacitor charging leads to a decreased chest compression fraction and delayed defibrillation. The lifesaving benefits of chest compression, together with those of early defibrillation, may be seriously compromised.[32,33] On the other hand, defibrillation parameters such as energy, current, and waveform duration are key variables that determine the defibrillation efficacy.[34–37] Although the low-temperature environment could cause a decrease in the delivered energy in some AEDs, this reduction was much smaller than the variation caused by impedance change in the same AED and the variation between different AEDs. Therefore, the suboptimal waveform parameters themselves may have a greater impact on defibrillation efficacy than the environmental factors.[34,38]

Understanding the feature characteristics of AEDs in all potential environments not only provides a basis for the design, manufacturing, and placement of AEDs but also provides assistance and guidance for the use of AEDs. Manufacturers can improve the environmental adaptability of AEDs by selecting components with strong environmental adaptability or packing the AEDs in insulated cases to keep the temperature above 0 °C if applied in low-temperature areas. Clinicians can choose different types of AEDs with good environmental adaptability based on operating scenarios, or adjust resuscitation strategies based on changes in the functional and electrical features to improve the resuscitation rate in extreme environments.

There are several limitations to the current study. First, there are many AED manufacturers and product models in the market, so the results of the investigated 6 AEDs might not necessarily represent the performance of all AEDs. Second, The ECG waveforms simulated by the defibrillator analyzer, rather than the actual patient's ECG signals were used to assess the reliability of shockable rhythms detection. This was somewhat different from the actual application scenario because the ECG signals of each patient were not the same. Third, in extreme environments, the charging capacitor, battery, and electrodes are exposed to the same harsh conditions and these components are also sensitive to temperature. However, neither the capacitor and battery temperatures at the moment of testing were measured nor the defibrillation electrodes were applied in the study. Fourth, as the actual time that each AED was exposed to the testing environment was different, the uncertainty of whether the AED had reached a "steady state" may affect the experimental results. Therefore, further clinical studies are warranted to elucidate

the impact of extreme environments on the outcomes of defibrillation and CPR.

Conclusion

All of the investigated AEDs functioned properly in simulated and natural extreme environments, but a large variation in the functional and electrical feature change was observed. The overall impact of low temperature on features of the AEDs was greater than that of the high altitude, and the impact of composite high-altitude and low-temperature extreme environments was mainly determined by the low temperature. When performing CPR in extreme environments, the impact of environmental factors may need consideration.

CRediT authorship contribution statement

Fangxiao Chen: Writing – original draft, Investigation, Formal analysis. **Yunchi Li:** Validation, Software, Investigation, Data curation. **Yushun Gong:** Visualization, Resources, Methodology. **Liang Wei:** Validation, Supervision, Project administration. **Juan Wang:** Resources, Conceptualization. **Yongqin Li:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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