Non-equilibrium air plasma for wound bleeding control

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Résumé

A low temperature non-equilibrium air plasma spray is tested as a blood coagulator. Emission spectroscopy of the plasma effluent indicates that it carries abundant reactive atomic oxygen (RAO), which can activate erythrocyte – platelet interactions to enhance blood coagulation for plug formation. Tests of the device for bleeding control were performed on pigs. Four types of wounds, straight cut and cross cut in the ham area, and a hole in a saphenous vein and in an artery of an ear were examined. The results were that this plasma torch shortened the bleeding time, for the first three types of wounds, from about 3 minutes to 18 seconds, from about 4 minutes to 25 seconds, and from 88 seconds to 15 seconds, respectively, as well as effectively clogged the hole in the artery to stop bleeding. The tests indicate that RAO can penetrate through the skin surrounding the wound to block capillary blood flow to the wound, making it fast to stop bleeding.

Bleeding, even from an external hemorrhage, may be life threatening if it is not treated swiftly [1]. Most cases occur under emergency situations. New methods and devices which can effectively stop bleeding could save the life of an injured person, especially in battlefield situations. Chen *et al*. [2] and Kuo *et al*. [3] showed that a low temperature non-equilibrium air plasma spray [4] could clot anti-coagulated whole blood samples in less than 20 seconds, which is much less than 30 minutes for an untreated sample to reach complete coagulation. It was also found via emission spectroscopy that this plasma spray carries abundant reactive atomic oxygen (RAO) in its plasma effluent [5]. Activation of erythrocyte – platelet interactions by RAO to trigger blood coagulation was suggested as a plausible coagulation mechanism.

However, those experimental results performed under well-controlled in-vitro conditions may not describe what occurs in the much more complicated in-vivo environment. In the present work, we use pigs as the animal model to perform *in-vivo* tests of blood coagulation by non-equilibrium air plasma. The feasibility and effectiveness of this plasma spray to stop bleeding are studied.

This device consists of a pair of concentric electrodes, a ring-shaped permanent magnet, a blower, and a power supply. A photo of the device with the generated plasma spray is shown in Fig. 1. A nozzle was introduced to direct the flow of the plasma effluent as well as to cover the electrodes for safety, so that the high voltage (HV) central electrode would not be exposed. An air pump was used to provide the airflow, which has a flow rate of 3 ℓ/s and an average flow speed of 24.5 m/s at the nozzle exit.

Fig. 1: A photo of the portable plasma spray.

The emission spectrum of the plasma effluent outside the nozzle from 300 to 900 nm was scanned by a spectrometer. In this spectral range, the UV radiation from 300 nm to 400 nm was not detected and the intensive lines contributed by oxygen radicals appear only around 777.4 nm, which were emissions from the 5P state of atomic oxygen (OI) in the plasma effluent. The average temperature of the plasma effluent outside the nozzle was measured along the axis by a thermal probe. The peak value in the temperature distribution is less than 328 K (55 ^{0}C).

Tests were performed on four three-month-old pigs, weighing around 25 kg. Three types of wounds, straight cut and cross cut in the ham area, and a hole in an ear saphenous vein, were introduced to two of those [6]. The other two were introduced a hole in an artery of an ear. The wounds introduced on one pig were treated by the plasma; the other pig was used as an untreated control so the bleeding from each wound was stopped by itself. The time it took for bleeding to stop naturally without treatment was considered to be the natural clotting (bleeding) time. Each pig was first

injected with calmative-Stresnil and fastened on a table. The pig was then anesthetized with Isoflurance-Fluothane which kept it in a narcotized state.

Test ---Hole in an artery : In this test the emergency procedure by using a tourniquet to tie the ear, where an artery was being cut, was first introduced. An artery from a pig ear was identified and cut by a scalpel as shown in Fig. 2a. It caused a severe bleeding as shown in Fig. 2b. The plasma spray at a distance of 2.5 cm was then applied immediately to the cut as shown in Fig. 2c. An intermittent treatment approach, running the device with 2s on and 4s off, was adopted. After on-off 6 times with a total plasma exposure time of 12 s, the cut was clogged and bleeding was stopped (in less than 35s) as shown in Fig. 2d. On the other hand, without the plasma treatment the bleeding would last for more than 60s.

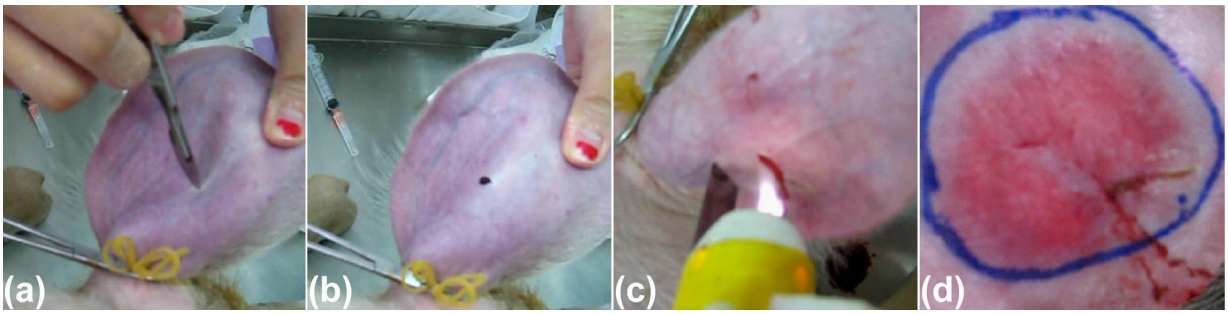

Fig. 2: (a) An artery in an ear of a pig is being cut, (b) bleeding from a cut artery, (c) plasma torch is applied to the cut, and (d) clogged cut after 35 s of intermittent plasma treatment.

The experimental results have shown that this plasma spray could rapidly stop bleeding. The atomic oxygen produced in the plasma effluent is likely the catalyst in the coagulation processes. When interacted with H_2O, atomic oxygen carried by the plasma effluent can produce large amount of reactive oxygen species (oxygen ions, free radicals, and peroxides). Studies have shown that platelets are a prime target for oxidants produced or released in the vascular lumen and, at the same time, they are also capable of endogenous generation of oxidants [7], [8]. It has also been shown that oxidants can affect several key steps of platelet function to enhance platelet aggregation [8]-[10].

It appears that the plasma treatment also produces a ring of pink color surrounding the cut as shown in Fig. 2d. It was found that this circular pink mark was independent of the wound and was not caused by a burn otherwise the inside area of the ring should suffer burn more severely. After about three days, this mark disappeared, and subsequently no other effect appeared in the exposed area in two-week observation. This suggested that this plasma spray would not cause any permanent effect on the exposed skin and tissues. This mark is likely attributed to the red blood cells accumulated underneath the marked skin. It suggests that the plasma effluent can penetrate the skin to block capillary blood flow into the exposed area. The blocked blood flow accumulates in the region surrounding the exposed area, showing a circular pink colored ring on the skin. Thus, the process of stopping bleeding by this plasma spray involves blocking capillary blood flow surrounding the wound as well as clotting the blood covering the wound. It explains why the low temperature non-equilibrium air plasma generated by the device can reduce the bleeding time drastically.

References

[1] P. Jevon, L. Cooper, Nurs. Times **104** (2008) 26.
[2] C.Y. Chen, et al., IEEE Trans. Plasma Sci. **37** (2009) 993.
[3] S.P. Kuo, et al., New J. Phys. **11** (2009) 115016.
[4] S.P. Kuo, US Patent No.: US7777151 (2010).
[5] S.P. Kuo, T. Pedersen, T. Mills, IEEE Trans. Plasma Sci. **36** (2008) 1056.
[6] S.P. Kuo, C.Y. Chen, C.S. Lin, S.H. Chiang, IEEE Trans. Plasma Sci. **38** (2010) 1908.
[7] A. Finazzi-Agro, et al., Biochim. Biophys. Acta **718** (1982) 21.
[8] D. Del Principe, et al., Thromb. Res. **62** (1991) 365.
[9] D. Del Principe, et al., FEBS Lett. **185** (1985) 142.
[10] D. Pratico, et al., Am. J. Physiol. **264** (1993) H1582.