ELECTROCHEMICAL HEALING SIMILARITIES BETWEEN ANIMALS AND PLANTS

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ABSTRACT A brief summary of the major results in enhanced wound healing by electrolysis in animals and humans is presented along with the results of enhanced growth by electrolysis in plants. Hypotheses of normal and enhanced wound healing in animal and plants are reviewed. A comparison of the experimental results indicates strong similarities in the optimum magnitude and polarity of the externally applied galvanic current in animals and plants. There are, however, differences in optimum current densities. There are strong similarities in animal and plant electropotential changes during normal healing.

The objective of this communication is to point out the similarities and differences in recent experimental results and hypotheses concerning electrically enhanced and normal wound healing in animals and plants.

ELECTRICAL ENHANCEMENT EXPERIMENTS

A substantial body of experimental and clinical results has been built up in recent years on the subject of electrically enhanced wound healing in animals and humans (Brighton, 1977). The enhancement techniques have taken two paths, depending on the method of impressing electrical energy at the wound site. In the first method an intrusive metal probe is placed in the healing site and electrical current passes between the probe and the tissue (Friedenberg et al., 1971). In the second method, based on electrochemical information transfer, a low frequency electromagnetic field is impressed at the surface of the tissue (Pilla, 1972; Pilla and Margules, 1977; Bassett et al., 1977). There is no surgical procedure. Both of these techniques have been applied primarily to bone healing in experimental animals and humans.

A definite pattern has emerged in the use of the intrusive probe technique. Healing enhancement occurs if electrolytic reduction takes place at the healing site. In electrochemical terms, the healing enhancement occurs if the cathode of the active galvanic cell is at the healing site. A theory has been proposed as to the biochemical action accompanying this electrolysis (Brighton and Friedenberg, 1974; Brighton et al., 1975). Brighton contends that at currents between 5 and 20 μA there is a reduction of oxygen at the stainless steel electrode surface. Currents in the order of 100 μA lead to voltages that shift the reaction to yield hydrogen evolution.

Now consider the results with plants. In an electrically mediated growth enhancement study, Black et al. (1971), using chloridize silver electrodes, reported that when the cathode was placed in the tissue of *Lycopersicon esculentum* cv. Scotia, the tissue contiguous to the surface of the electrode appeared normal. When an anode was placed in the wound site, tissue damage always appeared. More specifically, in a second season of testing (1969), the plants receiving 15 positive μA (current direction basipetal) showed severe cell damage around the probe within 72 h, while the plants receiving 15 negative μA (current direction acropetal) showed no injury. The interpretation of this result must be tempered, however, because of the attendant disintegration of the probe under positive currents only. The return electrode in this study was initially a single electrode; later multiple chlorodized silver wire electrodes were placed in the soil.

The current levels found to be effective for overall growth enhancement were between 3 and 15 μA; the current direction was acropetal. Current magnitude above 30 μA resulted in a reduction of growth.

The author tested the influence of current direction on the stems of freshly planted cuttings of *Citris jambhri, Lifh.* By using cadmium-plated metal clips as a nonintrusive tissue electrode and stainless steel as a soil electrode, 12 plants were tested at 0.3, 0.6, and 0.9 $\mu A/mm^2$ (6 with acropetal and 6 with basipetal current). In all cases, the tissue in the vicinity of the tissue probe with basipetal current became necrotic within 24 h. The tissue in all 6 plants with acropetal current experienced no damage other than a slight callousing believed due to the pressure of the clip. In additional testing (10 plants) of the influence of current direction on the same plant, a basipetal current of 1 $\mu A/mm^2$ for 24 h caused severe necrosis, while the acropetal current caused a slight callous formation believed to be a mechanical effect of clip pressure. The contrast in the tissue response to current direction for the same plant is shown in Fig. 1. The degree of tissue damage as measured by area surface discoloration was roughly proportional to the product of the current magnitude times the duration of application, a result also in basic agreement with Black's findings.

While the current magnitude encountered in stimulation of osteogenesis is similar to the magnitude of current in plant growth stimulation, the similarity of current density is another matter. Because of a precipitate build-up on the cathode in animal experiments, the effective surface area is questionable (Brighton et al., 1978). Measurements taking into account the precipitate indicate that effective current densities from 90 to 180 $\mu A/mm^2$ produced the same amount of bone formation while densities of 212 and 425 $\mu A/mm^2$ produced necrosis. These values are in contrast to current densities calculated by the author in the Black study of 0.9 $\mu A/mm^2$, based on an area of 16.3 mm^2. The author encountered consistent necrosis in freshly planted cutting of *Citris jambhri, Lufh* at a basipetal current density as low as 0.03 $\mu A/mm^2$ (0.5 μA total current) and no tissue damage at acropetal current densities as high as 1.9 $\mu A/mm^2$ (30 μA total current).

The comparison of the plant and animal growth results must also be examined in terms of the galvanic circuit path. In the human work the circuit path is from a cathode placed between the fracture ends to an anode located in the same region or in a region remote from the

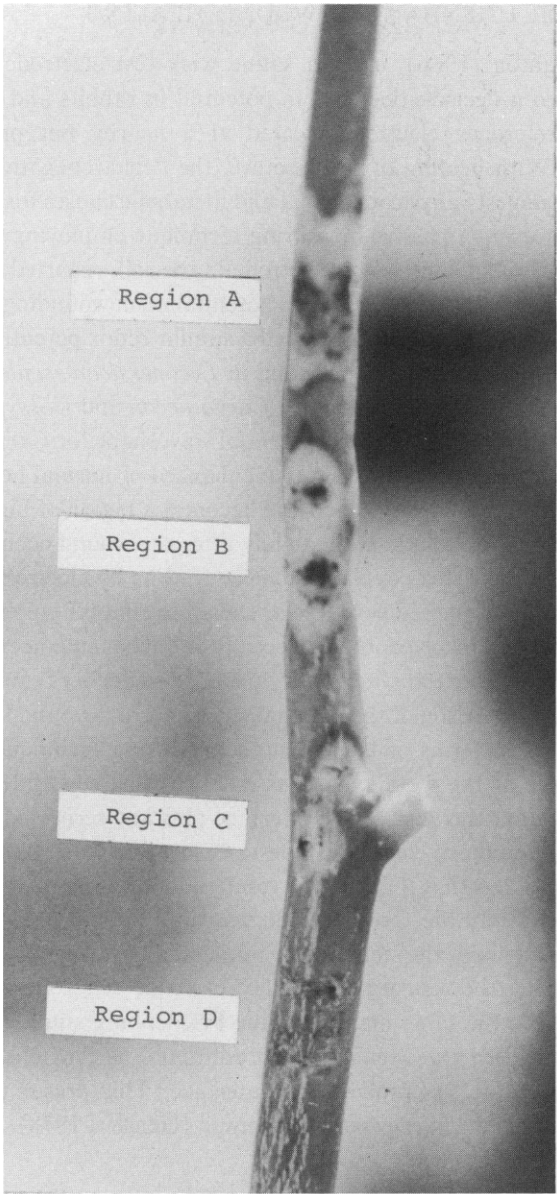

FIGURE 1 Potted cutting of *Citris jambhri, Lufh* subjected to galvanic current. Cutting length, 15 cm, cutting diameter, 5 mm. 15 μA basipetal current (1 $\mu A/mm^2$) was applied for 24 h at region A, then for 24 h at region B, then for 24 h at region C. After this, 15 μA (1 $\mu A/mm^2$) acropetal current was applied for 48 h at region D. The photo was taken 1 wk after the last application of current.

fracture site. Growth enhancement occurs in the vicinity of the cathode and is measured as a build-up of new bone tissue. In Black's study, the circuit path was from a cathode placed on the main stem, down the stem to anodes located in the soil. Growth in the Black study was measured in terms of specific element concentration change on a total plant basis.

NORMAL OR UNENHANCED WOUND HEALING

Friedenberg and Brighton (1966), using a saline wick test electrode on the skin above a fracture site, measured a decisive decrease in potential in rabbits and humans, relative to a second saline wick reference electrode located at a nearby but presumably indifferent electrochemical site. With healing of the fracture, the "electronegativity" reverted back to normal. Friedenberg suggests physicochemical and metabolic causes for this electronegativity. Gensler (1974, 1978), using a passive measuring technique employing a palladium electrode at the wound site and an AgCl reference electrode in the soil, reported that the plant healing process was manifest in an initial drop in redox potential upon wounding and a subsequent rise in potential during healing. Rewounding yielded a similar redox potential waveshape but on a shorter time scale. The same results were found in *Lycopersicon esculentum* and *Kalanchoë blossfeldiana* in the laboratory and in mature *Carya pecan* and *Gossypium hirsutum* in the field. Fig. 2 shows a typical rewound redox potential waveshape for *Carya pecan*. This pattern suggests a hypothesis of unenhanced healing: unenhanced or normal healing is characterized by a sequence of events in which the wound site becomes a region of high energy availablility manifest by a powerful redox couple immediately after the wound occurs. Healing is then an ordered consumption of the redox couple. Enhanced healing by electrolysis may be a result of increasing the availability of the redox couple or energy availablility present at the wound site. The exact couple or couples involved in this electrolysis during enhancement are unknown.

While the measured potential variations in the Friedenberg and Gensler study are strikingly similar, the comparison of the unenhanced or normal wound healing results in these studies should be made in terms of the potential measuring technique. In the Friedenberg study the test electrode at the wound site was a saline wick electrode which would yield a liquid junction potential at the wick-tissue interface plus any series galvanic potentials along the return path to the reference electrode. The test electrode was relatively remote from the fracture. The presumption is that the fracture resulted in a volumetric region of "electronegativity." In the Gensler study the test electrode was a palladium rod which would yield the redox potential of the region of the stem or leaf immediately contiguous to the rod. Any series galvanic potentials along the return path to the reference electrode would be algebraically added to this potential in the same manner as the Friedenberg study. The probe penetration into the stem or leaf caused the wound. The presumption is that changes in the measured potential reflect changes at the probe-tissue interface. This presumption is supported by evidence of potential shifts during rewounding stimuli (Gensler, 1978).

SUMMARY

In both plants and animals, the cathode or electrode at which electrons move from the electrode into the tissue via electrolysis was found to yield the most desirable electrode-tissue interface. The optimum current magnitude and polarity is comparable in both cases. However, the current densities are substantially different.

In normal healing in both animals and plants, a decisive shift to a negative potential is measured at the onset of the healing process followed by a gradual return to the base potential level. The results of passive measurements in normal plant healing point to a hypothesis of

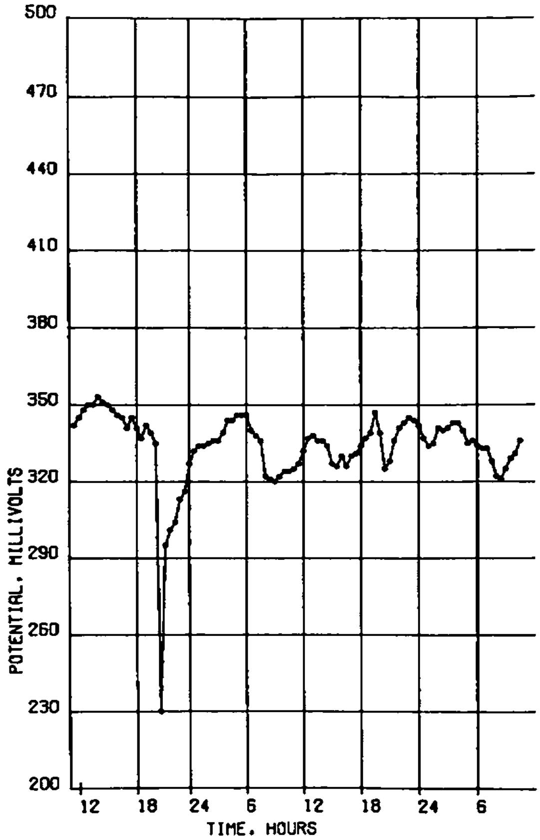

FIGURE 2 Typical electropotential recovery after rewounding of *Carya pecan* under field conditions. Rewounding was initiated by a blast of zinc sulphate solution under high pressure impinging on the monitoring probe wire. The palladium monitoring probe was placed in the stem just behind the nutlet. Original wound on day 0; rewound on day 14. Potential is with respect to an Ag/AgCl reference electrode in the soil. Disturbance occurred at 2030 h. The tree height was 11 m.

electrolytic reduction as a method of enhanced plant healing. Clinical results in animals and humans indicate that enhanced healing by electrolytic reduction does indeed occur.

Within the scope of these similarities it is important to approach further comparisons in the proper bioelectrochemical context. The surface area and electrode material in active stimulation must be taken into account since the type and extent of electrolysis depends strongly on both parameters. Comparison of results in the same animal tissue is at present impossible because of this problem (Pilla, 1974). Furthermore, whether the same type of stimulation affects different cell lines in a similar manner has yet to be determined. In passive measurements of normal healing, the electrode type and potential source along the total circuit path must be examined.

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