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ABSTRACT

Two radiotelemetric systems were developed for remote monitoring of body temperature in livestock. A battery-powered transmitter system was developed as a laboratory tool for remote continuous monitoring of ear-canal temperatures in animals used in vaccine trials and in studies of livestock diseases. An automated data-recording and processing system was also developed. Pilot studies in cattle indicate that the system will be a valuable quantitative tool for vaccine testing and animal experiments.

A second telemetry system was developed for widescale use in the livestock industry. It relies on an implantable passive (no batteries) transponder that is energized by an external source of microwaves to transmit temperature and decimal digit identification to a remote receiver. The animal identification feature, coupled with computers, offers the livestock producer unprecedented capabilities for efficient management of his operation.

The temperature feature of transponders can aid in disease detection and control, disease diagnosis, and stress and ovulation detection. Its use for identifying temperature markers in disease and stress-tolerent breeding stock may be valuable in selective breeding programs.

Electronic identification and temperature monitoring is now ready for field testing. Private industry is being encouraged to participate in field testing and commercialization of the concept.

INTRODUCTION

Radiotelemetry is an important development for the study of temperature phenomona in unrestrained animals. Its potential for the study and control of animal diseases prompted an interagency agreement between the United States Department of Agriculture, Animal Plant Health Inspection Service (USDA-APHIS) and the Energy Research and Development Administration (ERDA) to develop, at the Los Alamos Scientific Laboratory (LASL), two radiotelemetry systems for monitoring body temperature in food animals.

One system is fashioned after previously-described telemetry devices in that the transducer and transmitter package, which relays temperature from the animal to a remote receiver, is powered by conventional batteries. To minimize the need for handling large amounts of raw data, an automated data recording and processing system was also developed. This system is being evaluated as a laboratory tool for studying diseases and for testing vaccines in livestock.

The second system developed relies on an implantable passive (no batteries) transponder which is energized by an external source of microwaves to transmit temperature and decimal digit identification to a remote receiver. The system was developed for wide scale use in disease control and animal identification.

In this paper we describe the two telemetry systems, show some experimental data, and offer suggestions on the future use of remote temperature monitoring and electronic identification in animal health management.

VACCINE EVALUATION

The Veterinary Services Laboratories in Ames, Iowa, are responsible for evaluating the safety and efficacy of vaccines in host animals. Many of the agents against which vaccines are made do not produce a clear-cut end-point in test animals, such as death, but rather clinical responses that are often difficult to objectify and quantify.

Since fever is objective, and is perhaps the best-known indicator of disease (1), it has been an important criterion for evaluating clinical responses of test animals in vaccine trials. However, temperature monitoring by conventional methods introduces temperature artifacts from the handling of animals and very few temperature measurements in a day are practical. Since the febrile response is highly amenable to continuous data acquisition by telemetric methods, we became interested in the potential of temperature telemetry as a quantitative tool for evaluating the efficacy of animal vaccines.

Methods

The single-channel radio-telemetric system for automated data acquisition and processing has been described elsewhere (15). A block diagram of the system is shown in Fig. 1. A thermistor probe is inserted into the animals' ear canal so that it comes to rest close to the tympanic membrane. This site was chosen for monitoring temperature because of its proximity to the thermoregulatory center in the preoptic region of the anterior hypothalamus (3). Changes in temperature alter the resistance of the thermistor which changes the resonant frequency of an oscillator circuit. The frequency signal from the oscillator circuit gates 'ON' a 150 MHz transmitter for about 200 ms during each cycle of the signal from the oscillator circuit. The time interval between bursts from the transmitter (0.3-1.5 s) relays temperature information from the animal to a remote receiver.

The RF burst from the transmitter is converted to an audio output signal. The audio signal is rectified and integrated to minimize spurious noise pulses and then is converted to a square pulse for input to the trigger circuit of a time interval meter. This meter digitizes the time interval between subsequent pulses and supplies a digital output to the recording system. An ancillary analog signal from the time interval meter is used to record the data on an analog recorder.

The time interval meter and a keyboard terminal with dual tape cassettes are interfaced to a microcomputer. The digital output from the time interval meter is transferred onto the digital tape cassettes by the microcomputer. The terminal has an acoustical coupler and can be used to transmit the recorded data over telephone lines to a large computer facility for conversion of time-intervals to temperatures.

The results from the analysis can be transmitted back to the terminal from the computer facility, printed for evaluation, and recorded on cassette tape where the data are stored for future analysis or for controlling a plotter.

Pilot experiment

A pilot experiment was conducted to test the remote temperature monitoring system as a tool for evaluating vaccines in cattle (15). A steer weighing 650 lbs. was intranasally vaccinated with a candidate vaccine for infectious bovine rhinotracheitis (IBR). A second steer of the same size was held as an unvaccinated control. Twenty-eight days after vaccination, both steers were intranasally challenged with $10^{7.0}$ infectious units of a standard virulent IBR challenge virus (Cooper strain). Remote ear canal temperature measurements were taken at 1 minute intervals and mean temperatures were computed for 5 m or 60 m blocks. The steers were housed in a high security building maintained at 18.5 ± 2.5^{o} C.

Figure 2 shows the normal continuous temperature record of the unvaccinated steer for a period of 7 days before challenge. A diurnal variation of about 0.5° C was observed that was independent of ambient temperature. Temperature minima and maxima usually occurred at 0500-0700 h and 1800-1900 h, respectively. Figure 3 shows that in addition to the diurnal cycles, there were also variations of higher frequency but usually of lower amplitude.

Figure 4 shows the temperature histories of the steers upon challenge with virulent IBR virus. Temperatures of the unvaccinated steer rose sharply from 48-72 hours after challenge and peaked at 96 and 120 hours. Except for the second day of infection, the diurnal variation continued during the febrile response. However, compared to the prechallenge variations, the amplitude of postchallenge diurnal cycles increased during the ascending phase of the febrile response. The short-term variations also continued during the febrile response.

The difference between temperature records of the vaccinated and unvaccinated steers (Fig. 4) demonstrates the protective effects of prior vaccination. The vaccinated steer developed a low-grade and short-lived febrile response with only minor changes in diurnal variations.

The results of this experiment suggest that continuous temperature monitoring by radiotelemetry could be a powerful tool for evaluating vaccine efficacy in cattle and probably other species. Computer integration of the areas under the response curves for individuals or treatment groups would provide highly quantitative evaluations of vaccine efficacy with regard to the temperature variable.

In addition to greatly increasing the quantity of data obtained, temperature telemetry permitted the measurement of parameters not possible by conventional methods of temperature measurement. For example, diurnal variations which are well-known in normal cattle (4), were perturbed in this experiment as a result of IBR infection. If this proves to be a consistent finding with IBR or other viral infections, it will be a useful quantitative parameter. Although our experiments were done in animals that were experimentally exposed and housed in security facilities, remote temperature monitoring would enable studies to be made in a typical environment where subjects are naturally exposed, e.g., in feed lots or transport vehicles.

Optimization of the system

Although the temperature monitoring system described above shows great promise, it still needs to be optimized. For temperature telemetry to be a practical tool for vaccine evaluation, it is necessary that animals be monitored in parallel rather than in series as was done in the above experiment. Consequently, the system was recently modified (13) to permit simultaneous monitoring of up to 10 animals at a time. A block diagram of the multi-channel system is shown in Fig. 5. The multi-channel receiver is located in the animal holding facility and is remotely controlled by the microcomputer which is located in the laboratory, about 400 yards away. The multi-channel receiver is a modified Regency "WHAMO" 10-channel scanner, model #ACT-W10. The receiver was modified so that any one of the 10 channels can be selected by the microcomputer. The microcomputer also controls the duration and frequency of measurements on individual animals.

The second improvement in the system, now underway, is a reduction in the size of the transmitter assembly. The first generation package (7,15) was relatively large and had to be mounted on the halter of the animal. The size and location made the package vulnerable to damage. The new assembly (Fig. 6) is small and light enough to be mounted directly on the ear pinna. This geometry should improve resistance to damage.

PASSIVE TELEMETRY

Variations in body temperature signal a variety of physiological events in healthy and diseased animals. A practical electronic device suitable for remote temperature monitoring on a massive scale in the livestock industry would be of great benefit in the management of animal health. Further, with identification numbers encoded in the same device, it could form the basis for a nationwide, computer-compatable livestock identification system with disease detection capability.

The potential of such a system for animal inventory and disease control led to the inception of an electronic identification and temperature monitoring project, at the LASL, which has been supported by USDA-APHIS and ERDA since early 1973. From this project, a subdermally implantable electronic transponder has been developed that can be remotely activated to transmit temperature and identification information back to a receiver in a few tenths of a second (8).

For the system to be practical for widescale use in the food animal industry, it needed to meet the following requirements (6): 1) passive (no batteries); 2) remote sensing (animal restraint not required); 3) capable of identifying individual animals; 4) error-free; 5) suitable for direct input into a computer; 6) long life; and 7) low cost. Available experimental data indicate that the passive transponder meets many, and perhaps all, of these requirements.

Principle of operation

The principle of operation (6) is illustrated in Figure 7. The interrogator sends out a beam of 915 MHz radio waves towards the transponder (Fig. 8). A small fraction of the microwaves penetrate the skin of the animal and generate enough voltage (about 1-½ volts) to power the transponder circuitry. The internal circuitry of the transponder is used to change the reflection of the transponder antenna with a frequency that is proportional to the temperature of the animal (19-22 kHz over the range of physiological temperatures). This relatively low frequency reflection is detected with the same antenna that sent out the interrogating beam. The animal identification number is transmitted in a binary format in which "ones" are represented by the temperature frequency and the "zeros" by one-half the temperature frequency. Signal mixing and suitable filters isolate the return signal from the powering beam, and the signal is subsequently decoded into identification and temperature.

The antenna constitutes the largest item in the transponder package (see Fig. 8). When operated near resonance, its length is proportional to the amount of voltage which can be generated to power the electronics. The present length of 10 cm was chosen to be compatible with present day circuit elements, biological radiation standards, and the frequency of the interrogating beam. The hybrid circuitry of the unencapsulated transponder shown in Fig. 8 takes up considerably more space than will be required by the integrated circuit chips in the production transponders. The final size and configuration of the transponder will be determined on the basis of the implant site on the animal and the need for installing the implant simply, without surgical intervention.

Technical developments

"Proof-of-principle" of an external transponder that had the desired functional properties was demonstrated to the US Animal Health Association in October 1973. A second system, tested in September 1975 with a hybrid circuit temperature-only transponder, showed that transponders would work under the skin. A third system, finished in September 1976, is considered a preprototype of a commercial system because it has optimum circuitry and will measure temperature to 0.1° C accuracy, but encodes only 1 000 numbers (3 digits).

This portable 1976 system has a battery power supply for the interrogator and a range of about 1 meter. A 10-meter range is expected in the commercial units.

Tissue reaction to the implant

Limited data indicate that within a few weeks after silastic-coated transponders are implanted, they become enclosed in a thin fibrotic capsule (14). Histologic examination of a capsule removed from a steer seven months after the implant was installed indicated that it consisted primarily of semi-mature, fibrous connective tissue and mononuclear cells. No inflammatory or pathologic tissue reactions were observed. These findings indicate that the transponder was accepted as an inert material (D. R. Cassidy and W. D. Taylor, unpublished).

Animal Identification

It is generally recognized that if electronic identification is cost effective, it will be quickly incorporated into the livestock industries. Therefore, it is important that the development of the commercial system meet the needs of the specific industries so that incentive is present for its incorporation. As it becomes widely accepted, the cost effectiveness is likely to increase. Some ideas on how electronic identification can serve the needs of various livestock industries have been reviewed before (5).

Livestock production needs. Livestock production is highly competitive, and many variables are beyond the producer's control. Drought, disease, and market fluctuations profoundly affect the producer's profit or loss. To stay in business, a producer must be a good manager. Electronic identification, coupled with computers, offers potential individual animal management at a level previously impractical because of the manpower required for manual record keeping and data handling.

Livestock identification code. Many different identification systems have been developed for specific uses. Most could be replaced by a single, secure, electronic identification number, recorded in local and regional data banks with appropriate data links. These data links must have provisions that will guarantee that all records are protected against unauthorized access.

Because future producers will practice individual animal managment, a code was designed that would permit identification of every major livestock animal in the world. The International Livestock Brand Conference suggested the coding scheme shown in Fig. 9 (2). The LASL electronic identification system is compatible with this code, and a number of livestock industry groups have indicated tentative agreement with it.

Dairy herds. Automation of dairies can be substantially increased, and costs can be reduced through automated data collection and processing. For maximum production efficiency, producers must evaluate each animal's input and output and select for propagation those animals with the highest production. Input of interest are food intake, age, medication, blood lines, lactation cycle, performance of ancestors, and previous production history. Outputs of interest are weight changes, daily milk production, butterfat content, health status, current vs. previous production, and performance of progeny of both sires and dams. Thus, it is necessary to monitor the animals frequently, inexpensively, and accurately, and to correlate the data with anticipated performance. Achieving low cost will require automated data collection and computer data processing. Electronic identification and temperature monitoring are well suited to this type of operation. Dairy industry experience will be applicable, with slight modification, to other segments of the livestock industry.

Automatic feed dispensers. Automatic feeding of high-protein supplements, in amounts correlated with the milk production cycle, is mandatory if expensive concentrates are not to be wasted. Because not all protein concentrates can be provided in the milking parlor for optimum utilization, automated feeding units now being introduced keep track of the amount of supplements allotted to and eaten by each dairy animal. Electronic identification can trigger the computer to dispense the proper rations.

Beef herds. Bull performance tests (food-to-meat conversion efficiency) can be run using this system. Frequent automatic weighing of all beef animals at watering troughs and other concentration points can provide an extensive data bank for performance calculations of entire herds. In fact, if the producer keeps extensive records, and couples them with the current livestock market, cost of feed, etc., he can accurately determine the best time to sell, breed, or change food rations.

Swine. Because the unit value of swine is generally considerably less than that of beef, the first application in swine will probably be for unambiguous identification of breeder stock. Automatic weighing of breeder animals during their early growth will permit selection for highest food conversion efficiency and rapid weight gains. Optimization of the system for swine will probably follow its successful field testing for cattle.

Application for other animals. Electronic identification can be applied to practically all animal species, and should prove a very useful, accurate identification system in existing registry programs, animal shows, and sales. The system would inhibit, but not eliminate, mislabeling of animals. Perhaps a special transponder with small antennas could be made for small pets; however, the interrogations (the identification process) would have to take place at close range.

Sales barns. Electronically-identified animals could pass through sales barns at less cost per animal because of greater record accuracy, shorter holding periods, and less expensive data processing by computer. It would also be possible to provide the prospective buyer pedigree data on each animal. These data could include health records, conversion efficiencies of other animals with the same blood lines, and other data that might reflect on the animals' performance as a breeder, milker, or meat animal. Using this information, the buyer could adjust his bidding to reflect his evaluation of the animal's potential. Therefore, animals with the highest production would be the first to be electronically identified.

Disease control. Animal disease control in the USA is predicated on detecting infected animals and treating or disposing of them. Because infected animals are often detected only after passing through livestock markets, many other animals exposed to the disease must be quarantined and tested. Current methods of monitoring animal movements through commerce are not optimum for efficient traceback after disease has been found. Electronic identification offers nearly error-free, high-speed, computer-compatible traceback.

The USDA has also supported LASL development of a disease detection system called the enzyme-labeled antibody (ELA) test. This serological test is expected to have wide application in detecting many different human and animal diseases. It is fast, inexpensive, sensitive, and suitable for automation; and it can be coupled with traceback.

TEMPERATURE MONITORING

The benefits of electronic temperature monitoring depend largely on the animal industry involved. Many ideas for applications were suggested in a previous review (14). Several of these are summarized below. For a detailed account of references, the reader is referred to that review.

Fever

Fever is a well-known corollary to infectious disease. Electronic detection of fever in animals at their source of production or as they travel through commerce can be a valuable tool for controlling epidemics. Temperature telemetry can assist in identifying sick animals early in the course of infection. This will facilitate the rapid isolation, diagnosis, and treatment of these animals. As a result of early isolation of diseased animals, potentially explosive outbreaks of infectious diseases might be minimized or even stopped. Should infectious disease be detected in animals as they travel through commerce, the electronic identity code would permit rapid computer traceback to the herd of origin. This capability could be instrumental in the control of epidemics.

Temperature telemetry can also be used as a diagnostic aid. Diagnosis of tuberculosis and Johne's disease can be made on the basis of an acute hyperthermic response which follows the injection of tuberculin. Figure 10 shows a continuous record of telemetered tympanic membrane temperatures of a tuberculous cow intravenously injected with tuberculin (R. D. Angus and R. Van Deusen, unpublished). The hyperthermic reaction began within minutes after the injection, peaked in 3.5 h and was over in 8 h. Temperature maxima were about 3.5° C above normal. As a diagnostic technique, temperature telemetry is appealing because it is reasonably rapid and requires only one handling of test animals.

Temperature telemetry would also be of diagnostic value for determining the optimum time for isolating causitive agents from infected animals. The use of temperature-telemetry by McVicar, *et al*. (10) revealed a temporal relationship between viremia and temperature in deer experimentally infected with foot and mouth disease virus. Thus temperature telemetry might be of use for rapidly identifying the best donors for diagnostic specimens.

Where the collection of continuous or semi-continuous temperature records is possible, the shapes of febrile response curves may be of diagnostic value. For example, infection of cattle with bovine virus diarrhea virus is commonly accompanied by a characteristic diphasic febrile response curve. Baldwin, *et al*. (2) have suggested several other diseases of livestock for which temperature profiles would be of diagnostic value.

Stress detection

The detection of stress in livestock by temperature telemetry would assist the stockman in identifying and, thus, removing or alleviating the stressor. The stress reaction is accompanied by a redistribution of blood from the skin and splanchnic regions into the main muscle masses. This results in changes in body temperatures. Figure 11 shows a semi-continuous temperature record of a steer with a subdermally implanted transponder. The steer was held in a room maintained at $18.5 \pm 2.5^{\circ}$ C. The data show an abrupt drop in skin temperature which coincided with caretaker activity in the animal's room. Thus, even limited arousal of the animal resulted in significant changes in skin temperature. From the data, it can also be seen that the drop in skin temperature was followed by an increase in deep body temperature. Early detection of such changes in body temperature of livestock could signal the need for corrective action to be taken.

Thermal stress. Heat stress is a major factor limiting production and fertility in food animals throughout the tropical and sub-tropical regions of the world. Since heat stress can be detected by characteristic changes in body temperature patterns, the recognition of impending stress by temperature telemetry could activate cooling devices for individual animals or alert the stockman to the need for mass-cooling on a herd basis. Marked benefits from articicial cooling of livestock in hot environments has been previously demonstrated (11, 12).

Reproductive physiology

It has been estimated that approximately eight million cattle in the United States are artificially bred but that this number might increase to thirty million if ovulation could be determined more reliably (2). A rise in body (16) or milk (9) temperatures at the time of ovulation has been demonstrated in cattle. This suggests that temperature telemetry may be a promising tool for determining the optimum time for breeding or artificial insemination.

SELECTIVE BREEDING

Objective methods are needed for identifying disease and stress-resistant breeding stock. Body temperature can be a useful measure of the severity of infectious disease. It may also reveal markers for stress or heat-stress tolerance. A capability for detecting these markers electronically can be a simple yet significant tool for selecting brood stock bearing desirable traits. A record of these traits, along with breeding and production records for electronically identified animals, will permit computer-assisted selection of brood animals with the best mix of traits.

TECHNOLOGY TRANSFER

The USDA-APHIS and ERDA have funded development of electronic identification and temperature monitoring because of the need for better identification of animals and of other valuable items. Experimental results show that the ideas are sound and are ready for field testing. Potential manufacturers and users are being encouraged to become involved in commercialization of the concepts and to participate actively in field testing. Development of uniform performance specifications for electronic identification systems has begun. These specifications are intended to guide industrial development along mutually compatible lines.

CONCLUSIONS

From the foregoing it can be seen that radiotelemetry has great potential for widescale use in food animal management and disease control and for laboratory studies of livestock diseases. However, much more work needs to be done before this potential is realized.

ACKNOWLEDGMENTS

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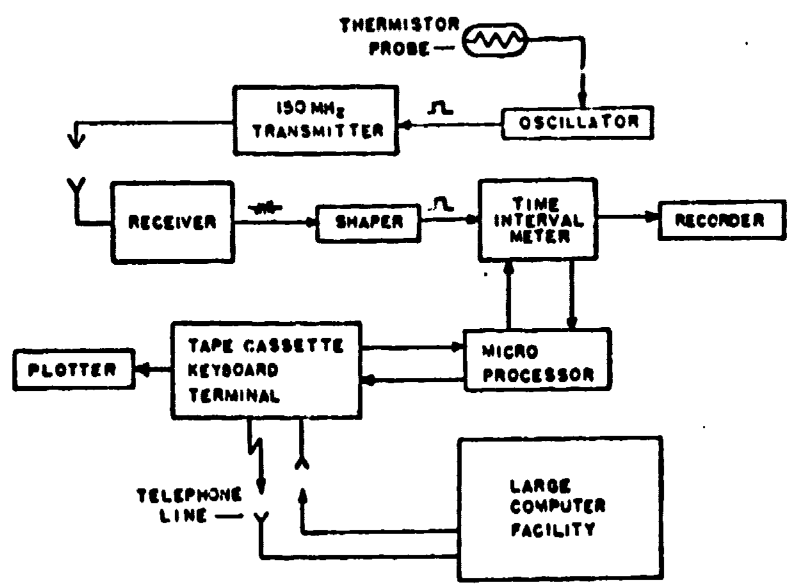

Fig. 1. Block diagram of the single-channel temperature monitoring system. The oscillator and transmitter are mounted on the animal's halter (from Seawright, et al. (15)).

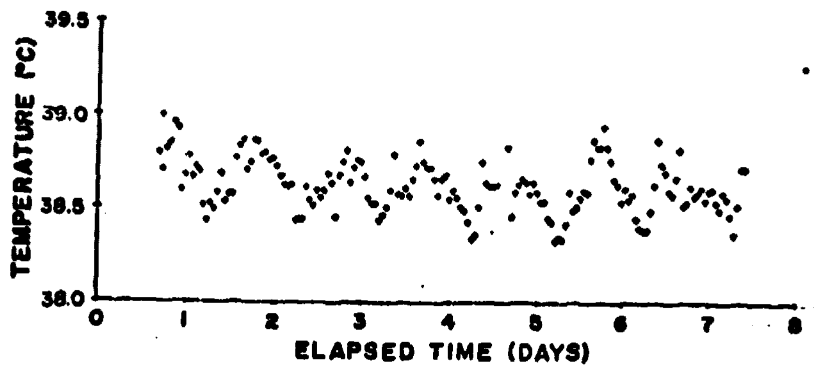

Fig. 2. Continuous remote ear-canal temperature record of a normal steer. Points are hourly means of measurements taken at 60 s-intervals (from Seawright, et al. (15)).

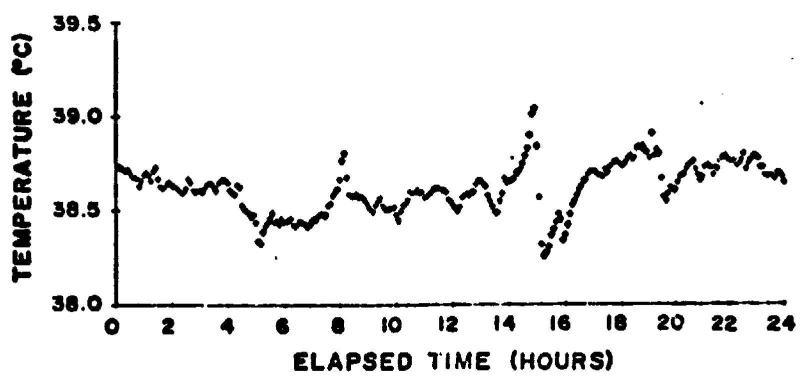

Fig. 3. Continuous ear-canal temperature record of a normal steer. Points are 5 m means of measurements taken at 60 s-intervals (from Seawright, et al. (15)).

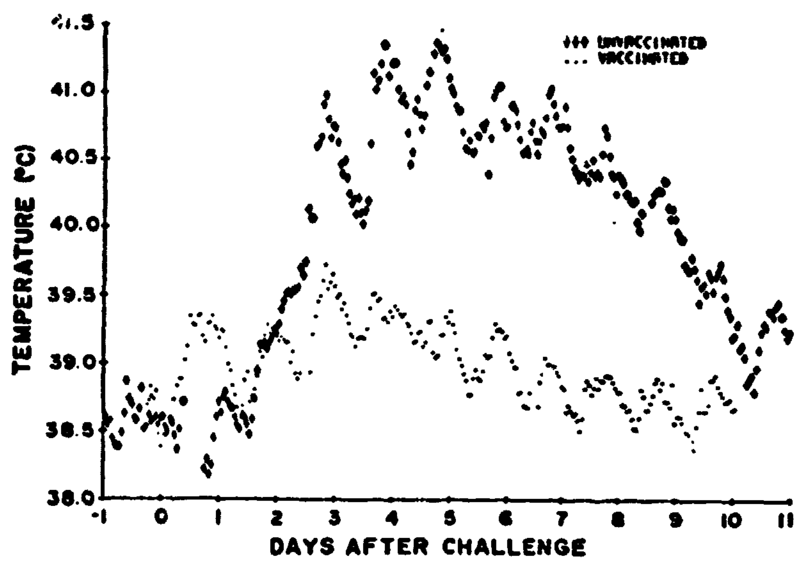

Fig. 4. Post-challenge temperatures of unvaccinated and IBR-vaccinated steers. Points are hourly means of measurements taken at 60 s-intervals (from Seawright, et al. (15)).

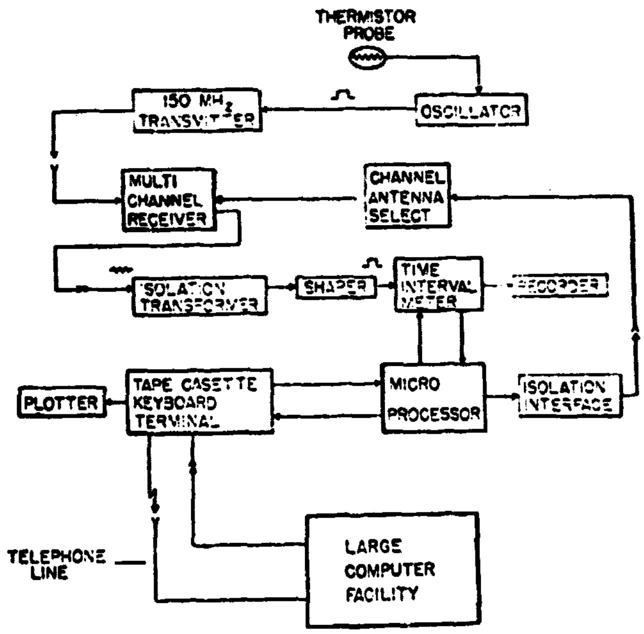

Fig. 5. Block diagram of multi-channel temperature monitoring system (13). The multi-channel receiver and channel and antenna select switch are in the animal holding facility. The remaining components of the system, excluding the large computer facility, are in the laboratory building, about 400 yards away from the animal holding facility.

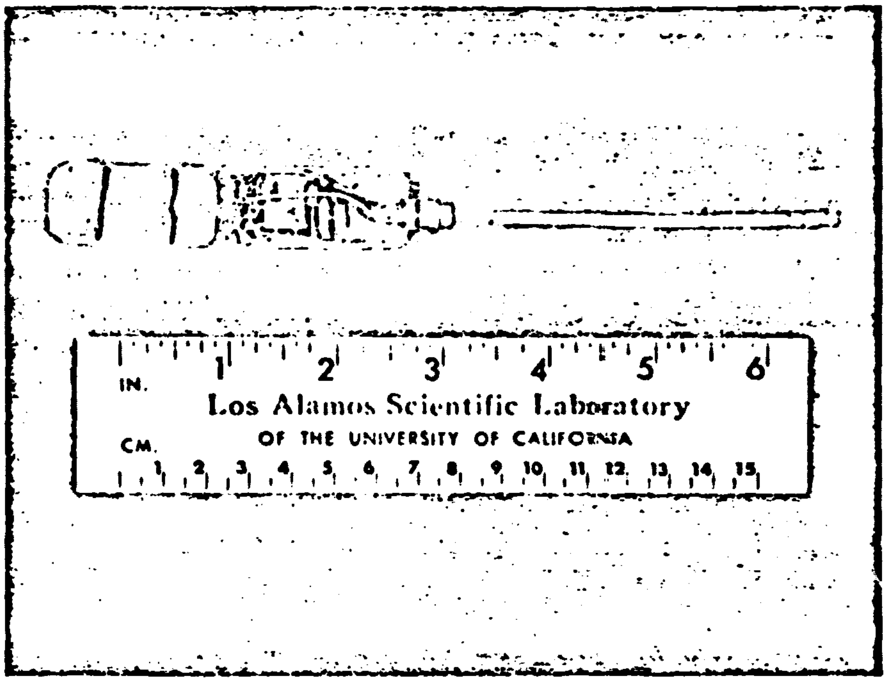

Fig. 6. Battery-powered temperature transmitter assembly for mounting on the ear pinna. Ear canal thermistor probe is shown on the right.

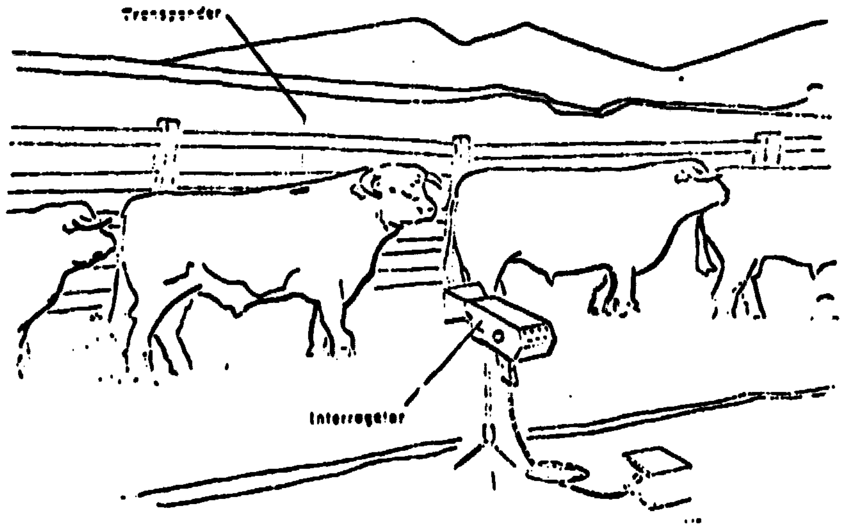

Fig. 7. Principle of the passive (no batteries) electronic identification and temperature monitoring system. The interrogator sends out a beam of microwaves that energizes the subdermal transponder. The reflection of the transponder is changed in an encoded manner to indicate the temperature and identification number of the animal. The encoded reflection is detected by the receiver, and the data can be indicated visually or sent to a computer for error-free reading (from Baldwin, et al. (2)).

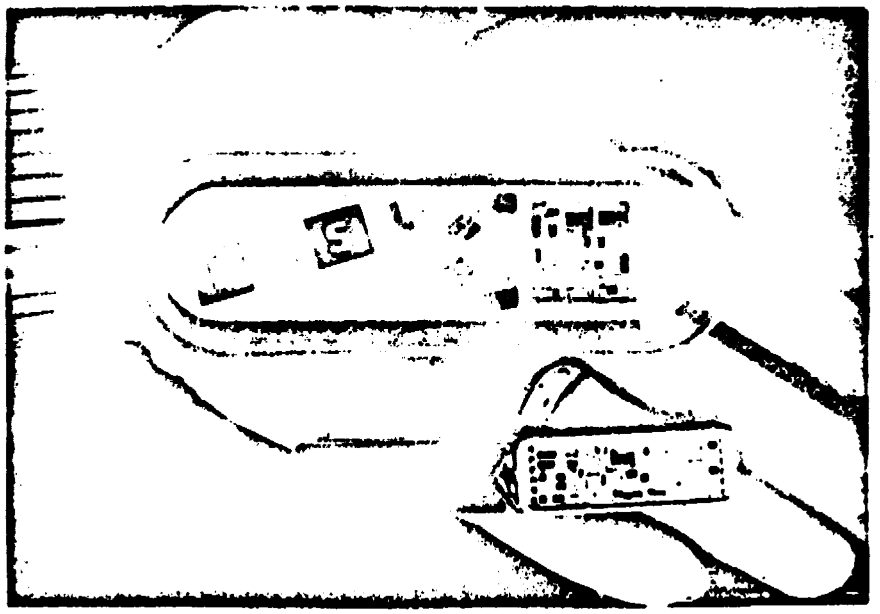

Fig. 8. Two models of electronic transponders. The top one is the 1975 model, which incorporated temperature measuring capabilities, but no electronic identification. A metal plate for hermetically sealing the transponder has been omitted to show the hybrid circuit elements. Actual implanted models of this unit are enclosed in an opaque encapsulant. As of November 1976, one transponder has been functioning under the skin of an animal for one year and six others for 11 months. No adverse biological reactions have been observed. The 1976 model transponder is shown at the bottom. This unit incorporates up to 1,000 identification numbers in addition to measuring temperature. It is also constructed of hybrid circuitry. Encapsulation is missing on the model shown, as well as the hermetic seal, which would enclose the electronics. The first implants of this model were accomplished in October 1976.

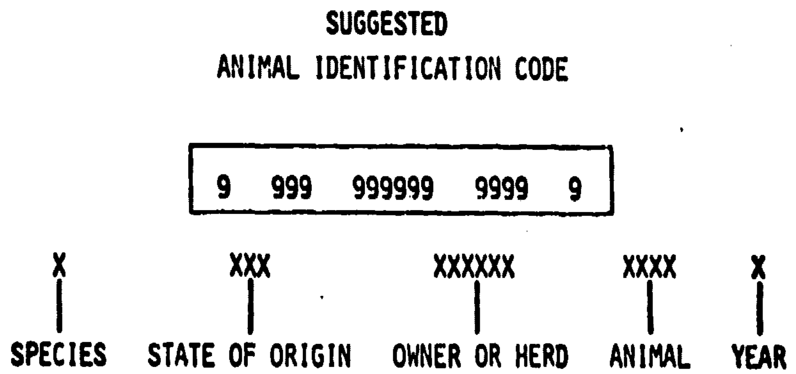

Fig. 9. Electronic identification coding scheme suggested by the International Livestock Brand Conference (from Baldwin, et al. (2)).

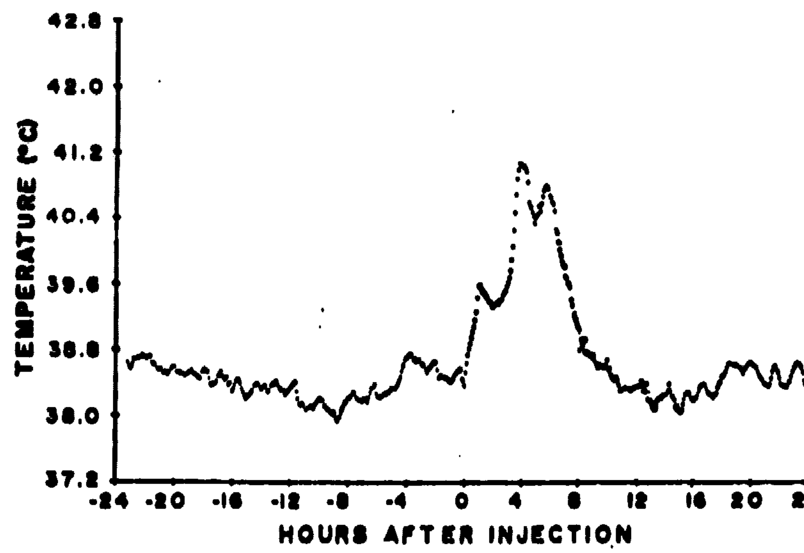

Fig. 10. Acute hyperthermic response of tuberculous cow after intravenous injection with tuberculin. Points are 5 m means of measurements made at 60 s-intervals (from Seawright (14)).

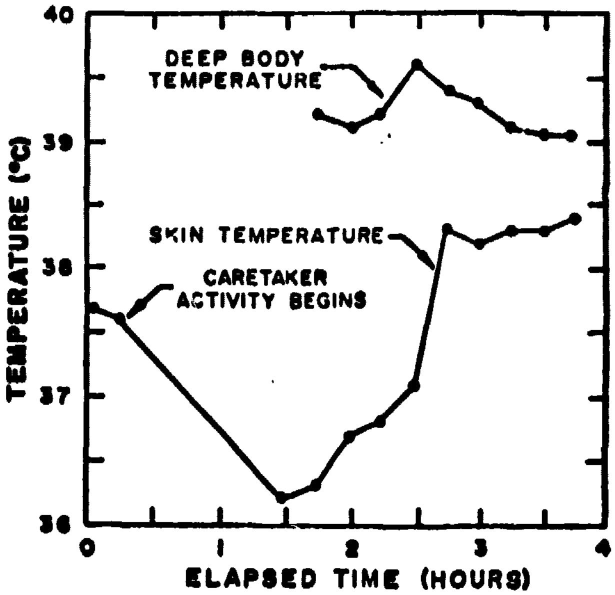

Fig. 11. Skin and deep-body temperature changes of a steer following caretaker activity in the animal's room. Skin temperatures were monitored with a subdermally-implanted transponder and deep body temperatures were monitored with an ear-canal thermistor probe (from Seawright (14)).

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