Measurements of transport based on temperature using the Arduino platform

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Abstract: The present capabilities of single-board microcontrollers make them appealing for both simple and complex tasks, including physics education and research. Learn how to use an Arduino board to conduct temperature-dependent transport measurements, starting at cryogenic temperatures and going all the way up to room temperature and beyond, in this article. Determining the sample temperature and measuring its resistance are two of the primary concerns for these types of research, and we address them both. Additionally, we describe two experiments that were carried out by students: one that demonstrated the magnetocaloric effect in gadolinium and the other that measured the resistive transition of a superconductor with a high critical temperature.

I.   Introduction

The development of single-board microcontrollers and single-board computers has given physicists access to a large variety of inexpensive experi- mentation that can be used either to design sim- ple test benches, to put together set-ups for class demonstration or to devise student practical work. Moreover, specifications of single-board compo- nents are now such that, although they cannot rival with state-of-the-art scientific equipment, one can nonetheless derive valuable physical results from them.

   We will here focus on the Arduino microcon- troller board [1]. Let us note that other boards, such as MBED, Hawkboard, Rasberry Pi, or Odroid to cite but a few, exist which may be cheaper and/or have better characteristics than Ar- duino. In our case, we have employed Arduino boards to take advantage of the important user's community. This has been an important selling point for the students with whom we are working.

   Indeed, our experience with Arduino is primar- ily based on undergraduate project-based physics labs [2] we have initiated within the Fundamen- tal Physics Department of Universit´e Paris Sud for students to gain a first hands-on practice of exper- imental physics. In these practicals, students are asked to choose a subject they want to study during a week-long project. They then have to design and build the experiment with the equipment available in the lab. The aim is not only to study a physi- cal phenomenon, but to do so by using inexpensive materials and low-cost boards.

In this article, we will describe two projects that have been developed by third year students. The first one aimed at quantifying the magnetocaloric

effect in Gadolinium and the second one, which has been popular amongst students, consisted in measuring the resistive transition of a high criti- cal temperature superconductor (HTCS). However, the techniques to do so can more generally be used for any experiment involving the measurement of a low voltage while varying the set-up temperature. In particular, they could be applied to simple trans- port characterization of samples in research labo- ratories.

In the following, we will focus on two important issues for this kind of measurements: thermome- try and thermal anchoring on the one hand, and measuring resistances on the other.

II. Determining the temperature of an object using microcontrollers

One of the experimental control parameters that is most commonly used to make a physical system properties vary is temperature. There is a wide variety of temperature sensors, depending on the temperature range of interest. The aim of this pa- per is not to list those, but rather, to focus on the most ordinarily found sensors compatible with an Arduino read out. We will also review some ba- sic techniques to ensure a proper thermal contact between the sample and the thermometer.

i. Sensors types

a. Built-in Arduino sensors

There are a number of temperature sensors that are generally sold with standard Arduino kits. The Arduino Starter Kit, for instance, comes with a TMP36 low voltage temperature sensor [3] (avail- able for about $1 if purchased separately) whose operating principle is based on the temperature- dependence of the voltage drop across a diode.

The advantage of this type of thermometer is that it can be directly plugged into Arduino with- out any additional electrical circuit. Furthermore, provided that the corresponding library is down- loaded, the temperature is straightforwardly read via the computer interface in °C, so that no cali- bration is needed.

However, these sensors are limited in accuracy and operation: the TMP36 sensor for example has a ±2°C precision over the −40°C to +125°C range

where it can operate. If they are extremely con- venient for non-demanding temperature read-outs, such as students atmospheric probes for example [4], they are not adapted to the precision needed for most research lab experiments.

b. Thermocouple

Thermocouples are cheap and robust thermal sen- sors that are industrially available for about $15, and which cover a wide range of temperatures (for example from −200°C to +1250°C for a type K thermocouple [5]). They are one of the few ther- mometers that are reliable at temperatures much higher than room temperature.

Thermocouples are also extremely convenient to measure the temperature of small-sized samples. Indeed, only the hot junction between the two met- als needs to be in contact with the region where the temperature is to be monitored. On the other hand, the quality of the readings will strongly depend on how thermally stable the cold junction is, and the temperature measurement is less precise than us- ing a thermistor. Indeed, the voltage to be mea- sured is small: the sensitivity of a thermocouple is of the order of tens of microvolts per Kelvin, and it decreases when the temperature decreases (a type- K thermocouple has a sensitivity of 40 μV.K^{-1} at room temperature but a sensitivity of 10 μV.K^{-1} at liquid nitrogen temperature).

Let us note that an amplification of the volt- age signal is then needed to read the temperature with Arduino. Some chips provide a ready-to-use thermocouple amplifier for microcontrollers (such as the MAX31856 breakout with a resolution of a quarter of a kelvin when using the Adafruit library [6] and an accuracy of a few kelvins). Better sensi- tivity could be achieved with a home-made ampli- fier (see below) and some care.

c. Platinum thin resistive films

Platinum thin films are practical and very reliable resistive thermometers typically working from 20 K to 700 K [7]. They are therefore suited for cryogenic applications – at least down to liquid nitrogen tem- peratures – as well as for moderate heating. The advantage of this sensor is that its response is en- tirely determined by the value of its resistance at 0°C [8]. The most commonly used platinum resis-

tance is the so-called Pt100 which has a resistance of 100 Ω at 0°C and costs approximately $3 to $5. These thermal sensors have a typical precision of about 20 mK up to 300 K and about 200 mK above room temperature. Moreover, their magnetic field- dependent temperature errors are well-known [7].

It is possible to mount those resistances on a dedicated Arduino resistance-to-temperature con- verter such as MAX31865 [9], but it is often sim- pler to plainly measure the resistance with a dedi- cated electrical circuit as will be explained in sec- tion III. This is particularly convenient for low or high temperature measurements for which the Ar- duino board cannot be at the same temperature as the thermometer and the sample are.

ii. Thermal anchoring

For the temperature measurement to be relevant, the thermometer must be in good thermal contact with the sample. How to achieve a good thermal anchoring is a subject of investigation in itself, but in this section we will outline a few standard tech- niques, focusing on the low temperature case.

To cool down a sample at low temperatures, one could use a Peltier module, but the simplest – and not so expensive – way is to use liquid nitrogen. Some basic safety measures have to be taken to ma- nipulate this cryogenic fluid: use protection glasses, gloves, work in a well-ventilated room and, above all, ensure that it is poured into a vessel that is not leak-tight to allow natural evaporation of liquid ni- trogen and avoid pressure build-up in the vessel. Once these precautions are observed, the manipu- lation is relatively safe.

To ensure that the thermometer indeed probes the sample temperature, the most obvious tech- nique is to solidly attach the thermometer to the sample using good thermal conductors. The ther- mal sensor can, for instance, be glued onto a cop- per sample holder. The glue then has to retain its properties at the probed temperature range. In the low temperature case, one frequently uses GE 7031 varnish which sustains very low temperatures and can easily be removed with a solvent. Alternatively, the thermometer could be mechanically fixed with a spring-shaped material whose elasticity is main- tained at a low temperature, such as CuNi sheets. Upon cooling, the spring-shaped material will con- tinue to apply pressure onto the thermometer, thus ensuring a good mechanical and thermal contact with the sample holder.

Another method is to thermally insulate the thermometer and the sample from the outside world, while putting them in contact with a com- mon thermal bath. This can be done by inserting them into a container filled with glass beads of a few millimeters in diameter [10] (inset of Fig. 7), or al- ternatively, sand. These materials provide a good thermal insulation of the {sample+thermometer} system from the outside world while allowing for an important thermal inertia. Moreover, when work- ing at temperatures close to 77 K, they limit the liquid nitrogen evaporation so that the tempera- ture increases back to room temperature only very slowly: typically for a volume 1 L of beads that is initially immersed in liquid nitrogen, the tempera- ture reaches back 300 K in 3 to 4 hours. The heat exchange between the sensor and the sample is then guaranteed through the evaporated N_2 gas, thus en- suring the temperature is homogeneous within the entire volume. An alternative method for achieving good thermal contact between the sensor and the sample through gas exchange is explained in Ref. [11].

III. Measuring resistances with mi- crocontrollers

Microcontroller inputs give a reading of electric potentials. Measuring resistances is then slightly more complicated than plugging a resistance into an ohmmeter. For educational purposes, this is ac- tually rather valuable since it gives students the opportunity to experiment with the notion of re- sistance and to realize that even the simplest mea- surement may present some challenge. In the fol- lowing, we will present standard methods to mea- sure resistances and we will particularly focus on the low-resistance case.

i. Current-Voltage measurement The simplest set-up for measuring a standard re- sistance is the

voltage divider set-up represented in Fig. 1: the resistance of interest R_0 is put in series with a reference resistance R_{ref}. The voltage drop across both resistances is controlled by the board 5 V output. The potential V_1 can be read by one
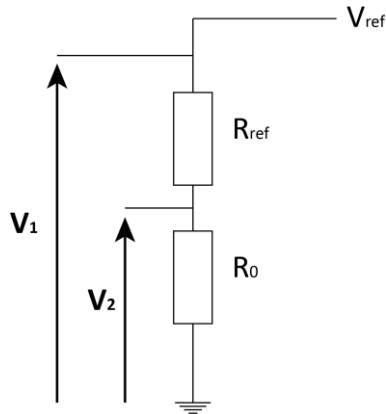

Figure 1: Schematic representation of the current- voltage set-up.

good precision (of the order of a few mΩ) by using a long string of copper wire (commercially available Cu wires of 0.2 mm in diameter have a resistance of about 0.5 Ω/m for example). However, unless V_2 is amplified, the precision of the measurement is not optimal. Moreover, using this method to mea- sure small resistances leads the circuit current to exceed the maximum current allowed at the micro- controller's output. In the following, we will see another method to measure small resistances.

ii. Wheatstone bridge

Another resistance determination method, which can achieve a good precision, is the Wheatstone bridge. The principle of the measurement is illus- trated in Fig. 2. R_1 and R_3 are fixed value resis- tances, while R_2 is a tunable resistance and R_0 the resistance of interest. The potentials V_1 and V_2 are then related

(2)
to 5 V. The potential V_2 – read by a second in- put – corresponds to the voltage drop across the unknown resistance. R_0 can then be determined through the simple relation:^{2} ^{1} $R_1 + R_2 R_0 + R_3{}^{e}$

The bridge is co-called "balanced" when R_2 is tuned such that V_1 and V_2 are equal. The resis- tances are then related through:

The monitoring of V_1 allows for a better precision through a direct monitoring of the current. Ar- duino's 5 V output sometimes varies in time. To have a better stabilization of the voltage, it may be useful to use an external power source for the micro- controller and not use the computer's USB output. Let us note that, if R_{ref} R_0, the current through the circuit can be considered to be constant, which is often very convenient when the resistance mea- surement does not require a large precision.

   This method presents several drawbacks when dealing with small values of R_0: since the ultimate resolution of an Arduino UNO board is of about 1 mV with V_{ref} = 1.1 V, one cannot measure R_0 smaller than about $2 \times 10^{-4} R_{ref}$. In the case of a standard commercial HTCS sample for instance, the normal state resistance is often of the order of a few tens of mΩ. To observe the resistance drop across the critical temperature T_c of a supercon- ductor, R_{ref} should then be of the order of a few Ω. Such resistances are commercially available or, alternatively, can be custom-made with a relativelyhe precision that can be achieved through this method and when using a microcontroller is about the same as for the current-voltage measurement method. However, this method is not very prac- tical when dealing with resistances R_0 that vary, since the bridge has to be maintained close to bal- ance at each measurement point. In particular, it is not well suited for the measurement of a super- conductor's resistive transition.

iii. Voltage amplifier

The most practical solution for the measurement of small voltages – and hence small resistances – is the amplification of the potential difference across the resistance. This can be done via standard voltage amplification set-ups using operational amplifiers, either in single-ended or differential input configu- rations. In the single-ended case, illustrated in Fig. 3, the output potential is given by:

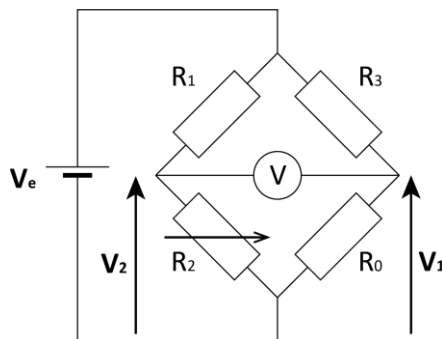$$V_{out} = \left(1 + \frac{R_2}{R}\right) V_{in} \qquad (4)$$

Figure 2: Schematic representation of the Wheatstone bridge: R_1 and R_3 are fixed resistances, R_2 is a tunable resistance, and R_0 is the resistance of interest.
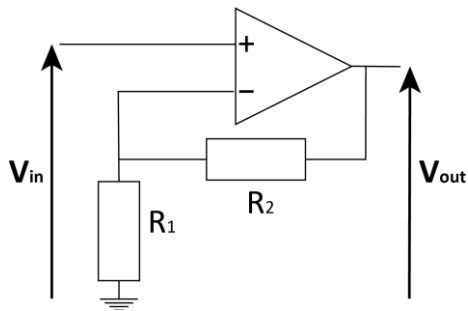
Figure 3: Voltage amplification.

The input voltage V_{in} can then be amplified at will, depending on the ratio $\frac{R_2}{R_1}$. The output voltage V_{out} can then be read by the microcontroller.

This amplification method has a much larger pre- cision than the previously mentioned methods, it does not require tuning at each data point and can be used to measure any small voltage: the volt- age drop across a superconductor, but also the dif- ference of potential across a thermocouple, or to derive thermoelectric coefficients (Seebeck or ther- mopower).

Going beyond this simple amplification method requires substantially more work. One possible method is to fabricate a microcontroller-based lock- in amplifier, as demonstrated in Ref. [12].

iv. Using another ADC than Arduino's

The specifications of Arduino Digital-Analog Con- verter are often the main limitation in the above measurements. As already mentioned, the Arduino ADC provides – at best – 10 bits on the 1.1 V in- ternal reference voltage, and can only measure a voltage in single-ended configurations.

One alternative would be to use another micro- controller, with a better ADC. For example, the low-cost FRDM-KL25Z from NXP [14] provides a ADC that can measure a voltage either in single- ended or in differential input configurations with 16 bits on 3.3 V.

The ease-of-use and the large users community can be a strong motivation to keep Arduino as your board of choice. In which case, a second solu- tion would be to use an external ADC when better resolution or a differential mode configuration is needed. For example, we have tested the ADS1115 chip [15]: this external ADC can measure 4 single channels or 2 differential channels with 16 bits on 4.1 V. The possibility of a preamplification up to 16 times brings the resolution down to 8 μV per bit instead of the standard 5 mV (or 1 mV with the 1.1 V internal reference).

The possibility of measuring a voltage in a dif- ferential mode configuration with a resolution bet- ter than 10 μV are two important advantages that open many interesting possibilities for physics mea- surements: for instance, measuring a strain gauge or a resistance in a four-wire configuration, or mea- suring directly a thermocouple or the resistance of a superconductor across the transition.

The main drawback to this method is that it is not as easy as using the Arduino ADC: a library should be installed first (but good tutorials can be found online, see for example Ref. [15]). Also, an external ADC is generally not as robust as the Ar- duino's ADC, and the user should carefully monitor the voltage input so as not to damage the ADC.

IV. Evidencing a magnetocaloric ef- fect with microcontrollers

To illustrate these methods, let us detail the mag- netocaloric effect that we have measured. This ef- fect consists in the temperature change occurring when a magnetic material is placed in a varying
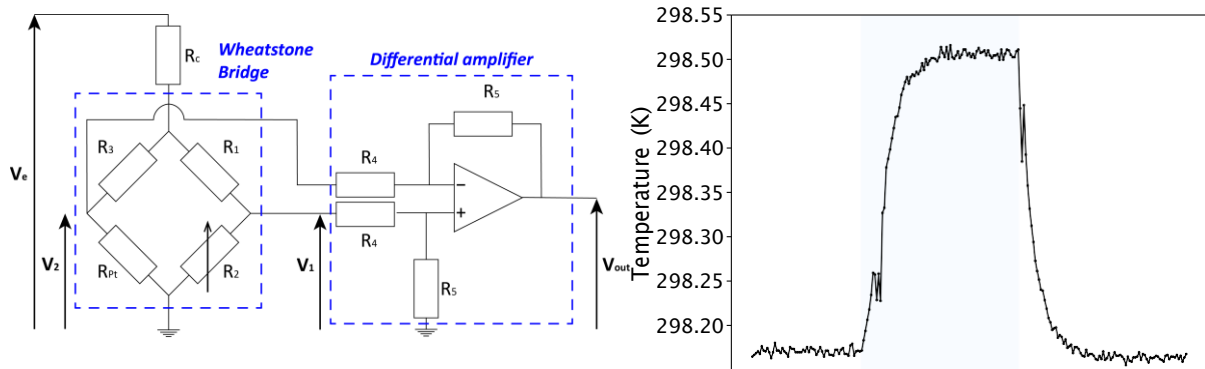
magnetic field. A more detailed explanation of this the phenomenon can be found in Ref. [16].

In our case, Gadolinium (Gd) was chosen for its paramagnetic properties and its Curie temperature close to room temperature (T_{Curie} = 292 K). At a temperature of about 298 K, a 2.242 g Gd sample was submitted to the magnetic field created by a neodymium magnet of maximum value 0.51 T.

In this experiment, the challenge was to measure the small temperature difference induced by the application of a magnetic field. To this effect, a Pt100 thermistor was put in good thermal contact with the Gd sample via thermal paste. The resistance change was measured by a Wheatstone bridge with the following characteristics: R_1 = R_3 = 100 Ω, R_2 has been set at 108 Ω to be close to balance at the considered temperature and V_e = 5 V via Arduino's internal source. An additional resistance R_c = 800 Ω was placed in series to limit the current going through the Pt100, thus avoiding heating the thermometer. V_e is then replaced by $\frac{R_1+R_2}{R_1+R_2+2R_c}$ V_e in Eq. (2). The off-balance difference of potential $V_2 - V_1$ was differentially amplified with a gain of 100 (R_4 = 1.5 kΩ and R_5 = 150 kΩ). The voltage V_{out} was then read by the board (Arduino Mega in this case) using 2.56 V as Arduino's ADC ref- erence voltage [17]. The overall read-out circuit is schematically shown in Fig. 4. The temperature is then inferred knowing that, in the [273 K - 323 K] range, the Pt100 response can be linearly fitted by:

$$T\,[\text{K}] = 2.578 R_{Pt}[\Omega] + 15.35 \qquad (5)$$

As illustrated in Fig. 5, the magnetocaloric ef-

Figure 5: Magnetocaloric effect in a Gd sample submit- ted to a 0.51 T magnetic field (blue background) be- fore going back to the zero-field situation (white back- ground). Each data point corresponds to the average of 50 measurements. The noise level is of the order of 10 mK.

fect is clearly visible with an amplitude of about $\Delta T \simeq$ 0.33 ± 0.01 K and a time scale of a few sec- onds. The resolution of the setup corresponds to 50 mK (18 mΩ). Each data point in Fig. 5 corre- sponds to an average of 50 measurements so that the effective noise that can be observed is of about 10 mK, or about 5 mΩ in resistance. This yields a relative precision for the measurement of a few 10^{-5}, which is remarkable given the simplicity of the apparatus . When the magnet is taken away from the Gd sample, the temperature decreases back to its initial value, as predicted by the isen- tropic character of the magnetocaloric effect.

V. Measuring a superconducting re- sistive transition with microcon- trollers

For the second experiment, we would like to detail is the measurement of the superconducting resistive transition of a HCTS. Indeed, in such compounds, the critical temperature T_c below which the sample is superconducting and exhibits zero resistance is larger than 77 K. The transition can therefore easily be observed by cooling the sample down to liquid nitrogen temperature and warming it back up to
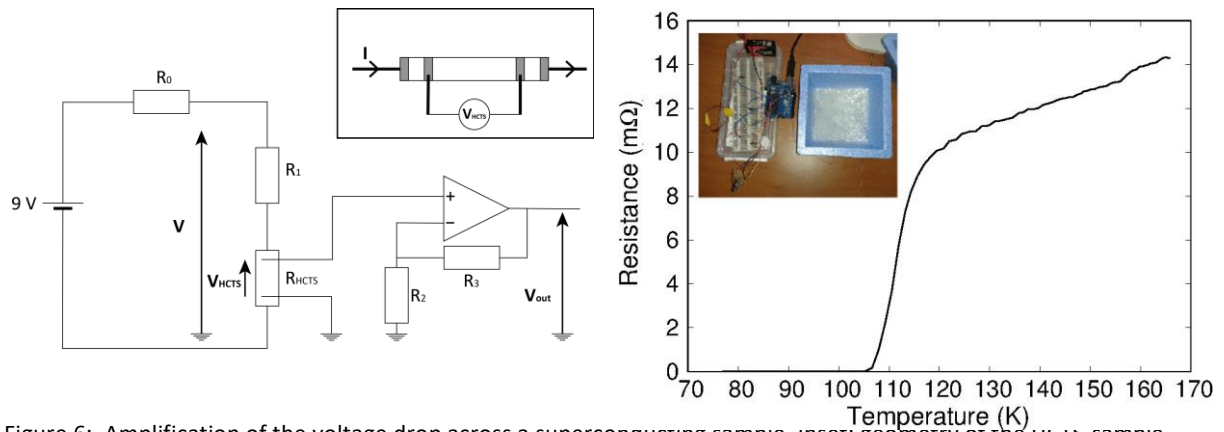
Figure 6: Amplification of the voltage drop across a superconducting sample. Inset: geometry of the HCTS sample.

room temperature.

In the present case, the HCTS is a commercial $Bi_2Sr_2Ca_2Cu_3O_{10}$ sample which specifications in- dicate a critical temperature $T_c = 110$ K at mid- transition point and a room temperature resistiv- ity of 1 mΩ.cm [18]. In this case, the experimental challenge is therefore to measure very small resis- tances with good precision. To achieve this, it is essential to adopt a four-wire measurement config- uration for the superconductor, as schematized in the inset of Fig. 6. Indeed, in this way, no contact resistances or connection wires contribute to the measured resistance. Moreover, the voltage drop across the superconductor has been amplified by a factor of 480 by a single-ended operational ampli- fier set-up as shown in Fig. 6. The current going through the superconductor is fixed by $R_0 = 110.0$ Ω ≫ R_1, R_{HCTS} and is experimentally measured via the potential V read at the extremity of a home- made resistance $R_1 = 1.18$ Ω, made out of copper wire.

The temperature has been measured with a Pt100 resistive thermometer using the set-up shown in Fig. 1 with $R_{ref} = 217.3$ Ω and a reference volt- age of $V_{ref} = 3.3$ V provided by one of Arduino UNO's internal sources.

Both the sample and the thermometer have been attached to a printed circuit board and have been wrapped in cotton to ensure temperature homo- geneity. The ensemble was placed in a polystyrene container filled with glass beads (inset of Fig. 7). Liquid nitrogen was then poured into the container

Figure 7: Resistive transition of a superconductor mea- sured with a voltage amplification. Inset: experimen- tal setup. The blue polystyrene container is filled with glass beads. Both the superconductor and the Pt100 thermometer are immersed inside with liquid nitrogen.

and the temperature of the ensemble was let to in- crease back to room temperature while recording the data.

In this manner, we have measured the resistive transition given in Fig. 7. The experimental data have been averaged by a convolution with a Gaus- sian of half width 0.4 K to take into account the error in the temperature measurement. As it can be seen, the resolution of the measurement is of the order of 0.1 mΩ for the superconductor's re- sistance. The latter is actually dominated by the thermal gradient that may exist between the sam- ple and the thermometer if the operator does not carefully check that both are close to one another or if the container is forcefully warmed-up (with a hair dryer for instance). Nonetheless, the precision of the measurement is good (< 1% relative uncer- tainty) and the measured mid-point T_c is of 112 K
± 2K, very close to the value given by the specifi-
cations.

VI. Conclusion

In conclusion, we have shown that standard tem- perature and resistance measurement methods could be adapted to microcontrollers. The perfor- mances that are then attainable are sufficient to probe with reasonable sensitivity a large range of

the phenomena of physics, including the effects of heat on resistivity, the Hall effect, the magnetocaloric effect, and many more. We have shown this by analysing the resistive transition of a high critical temperature superconductor and the magnetocaloric effect in gadolinium. We think that the range of accessible, low-cost, easily transported, and constructed tests made possible by single-board microcontrollers is ever-expanding and, in some instances, may now replace conventional laboratory characterisation methods. In addition, they provide a plethora of chances to come up with creative classroom activities that get kids more involved.

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C. A. M-K., M. M., B. P. and Q. Q. have super- vised and coordinated the studies. All authors have contributed to the redaction of the paper.

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