Journal of Applied Physics

RESEARCH ARTICLE | AUGUST 08 2025

Underground muography measurements by the HUN-REN Wigner Research Centre for Physics

Special Collection: Muography: Discoveries, Innovations, and Applications

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J. Appl. Phys. 138, 064903 (2025)
https://doi.org/10.1063/5.0273449

Journal of Applied Physics | ARTICLE | pubs.aip.org/aip/jap

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Cite as: J. Appl. Phys. **138**, 064903 (2025); doi: 10.1063/5.0273449
Submitted: 31 March 2025 · Accepted: 19 July 2025 ·
Published Online: 8 August 2025

View Online Export Citation CrossMark

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Note: This paper is part of the Special Topic on Muography: Discoveries, Innovations, and Applications.
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ABSTRACT

In recent years, there has been continuous development of muographic instruments at the HUN-REN Wigner RCP, including hardware and software. In addition, field testing was performed at several underground sites, looking for new geological understanding. Transferring the particle detector technology from the laboratory to real field conditions presented many surprises and problems to solve, and despite significant progress, there are still newer and newer challenges to overcome. In this article, we summarize recent developments and show examples of results of field measurements carried out in both Hungary and other countries. As of now, muography projects are being carried out in five countries with more than ten detectors, offering promising new insights. This article is based on the presentation given by the corresponding author at the 2024 Muography Workshop held in Santa Fe, NM, USA.

INTRODUCTION

Muography is an imaging technique that, in the current decade, is increasingly moving from the research phase to the application phase. Cosmic radiation on the surface of the Earth is a natural phenomenon known for more than a century, based on the discovery of Theodor Wulf.[1] Muons are generated in the high atmosphere mainly by the interactions of the primary cosmic ray proton component with the nuclei of the atmosphere.[2] The practical use of muons for geophysical and archaeological purposes started in the 1960s, but the real breakthrough came in the early 2000s, when the detector technology became simpler, cheaper, and thus more widely available.

The cosmic ray muons are high energy charged particles that lose energy as they pass through matter in a well-defined way. The reduction of the muon flux is proportional to the integrated density along the muon path, similar to the x-ray radiography; thus, the muon flux in a given depth mainly depends on the density distribution of the material above the detector and the zenith angle of the muon path.[3] This, and the fact that the muons travel along nearly a straight line up to the stopping point,[4] allows the density distribution of the volume above the detector to be investigated with high resolution tracking detectors.

Muon tomography or muography has been successfully applied in recent years, such as to identify density increase due to an ore body,[5] and decrease due to cavities,[6–8] or to image the internal structure of a volcanic cone[9] or a nuclear reactor.[10]

The field of muography research began almost 20 years ago at the Wigner RCP, initially using the CCC (Close Cathode Chamber) multi-wire technology,[11,12] and later developing the advanced MWPC (Multi-Wire Proportional Chamber) technology.[13] Since then, numerous geophysical results have been achieved.[14] The first setups were intermediate designs between laboratory instruments and real geophysical tools, making them barely suitable for extended field measurement campaigns. Thanks to continuous development and parallel field tests, some of the instrumentation has now reached Technology Readiness Level (TRL) 7, and extensive experience has been gained to better prepare for and conduct field measurements.

HARDWARE DEVELOPMENT

The MWPC type detectors developed by Wigner are high resolution portable trackers, which can be used in an out-of-laboratory environment too. The detectors generally contain eight chambers, and the ratio of the wire distance and the chamber spacing allows to reach the 0.5°–1° angular resolution, depending on the detector type. Thanks to the low power (~10 W) and gas consumption (<1 l/h), the detectors can be operated in real field conditions, even in difficult-to-reach part of caves or other underground facilities.

One of the most challenging places to carry out geophysical measurements is an active mine, where both the geological conditions and the circumstances due to the continuous production of the mine can make the collection of data very difficult. Under these conditions, we had to work in a copper mine in Lubin, Poland, where the temperature was more than 35 °C, the humidity was 100% of corrosive moisture, and the long underground transportation caused unusually strong vibration of the detector. Despite the harsh conditions, the original setup, which had previously been used in other mines (see Holma *et al.* in this volume, Ref. 15), started to measure normally; however, we experienced degradation of the system after several weeks of operation. We tried various methods to reduce the ingress of aggressive vapors in the instrument, but it was determined that only a radical improvement could solve the problems in the long term. In order to fully isolate the detector from the environment, a stainless-steel casing was manufactured (Fig. 1), and a long hose was installed on the gas outlet[16] in order to keep the atmosphere clean inside the steel box. The system had to remain open; otherwise, it would not have been able to withstand the rapid pressure changes during the mine shaft transport. After these developments, the detector completed the one year long measurement campaign without any problems.

FIG. 1. An "Mtl" type MWPC detector with stainless steel casing. In front of the detector, the gas system and the power box can be seen. The active size of the chambers is 80 × 80 cm^2.

Despite difficult conditions in deep mines, this is not the most challenging environment for a muography measurement. The HUN-REN Wigner RCP is being involved in the "Mine.IO" Horizon Europe project, where one of the goals is to develop a fully underwater detector to be able to carry out muography measurements in flooded mines or other underwater environments. In this development, the Wigner is in strong collaboration with INESC TEC Institute (Portugal) and Muon Solutions Ltd. (Finland). The first prototype of the detector was completed in mid-2024, and the first underwater test measurements are currently being performed. The MWPC type detector[13] was built in an anodized aluminum cylinder with an outer diameter of 200 mm and a length of 600 mm. The setup contains four chambers with a sensitive area of 128 × 384 mm and 4 mm wire spacing (Fig. 2). In the first model, only the detector chambers were installed in the cylinder; the electronics and the battery were placed into another similar cylinder (Fig. 3). However, in the second prototype, all electronics will be placed into the same cylinder as the chambers, and the other cylinder will be solely for the batteries, which will increase the current 4 day operation time by a factor of 3–4.

The most challenging part is the gas supply. While the power can easily be supplied by a larger watertight battery pack or even from the surface via cable, providing the continuous gas flow generally required by the MWPCs would be a more serious problem. In order to skip this, the detector was designed and built to be able to operate in sealed mode, without continuous gas flow for at least as long as the batteries can provide the power. This requirement was amply met by the detector in the first open tests, when the stable operation period was 4 weeks, and a slight degradation of the gas quality was observed just after a month (Fig. 4). The flux change is a combination of the long known barometric effect (−0.2%/mbar) and reduction of gas quality.[17] After installation of the chambers in the cylinder and a thorough flushing, the situation improved further. Currently, the system has been in stable operation for three months, and no decrease in efficiency has been observed (Fig. 5).

SOFTWARE DEVELOPMENT

Parallel to hardware development, intensive software development is also under way. In order to uniformly handle the data

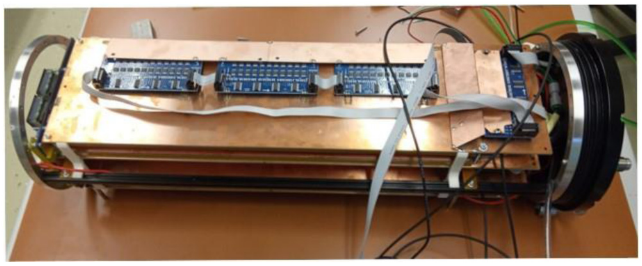

FIG. 2. The four-layer chamber setup with the readout electronics.

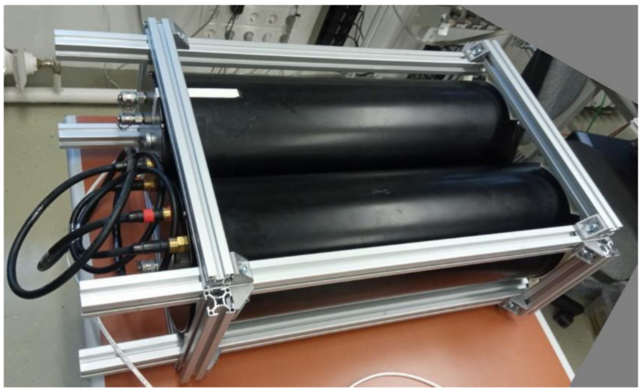

FIG. 3. The underwater detector cased in the aluminum cylinder together with the electronics and battery module.

produced by different detectors, a framework and a database manager were developed to process measurement data. This software system generates a unified file called a "muogram," which contains the results in an angle-binned format from: (1) the tracking software module (number of tracks, flux, etc.), (2) the flux conversion module (density-length), and (3) the geometry module (rock length, known void length, etc.). As a result, this unified file can be visualized in 2D or used as input for 3D tomographic inversion.

The most important improvement was in the field of the 3D tomographic inversion.[18] A Bayesian (L2)-type[19] discrete tomographic inversion software has been developed on the MATLAB platform. The Bayesian inversion can include geological and topographic constraints, with spatial dependencies to compensate for estimation bias. Matrix inversion is performed using LU decomposition[20] with a large voxel number. Alternatively, an L1-type Bayes condition can be specified and solved by Lasso-iteration. The package is also capable of performing 2D inversion, which can be

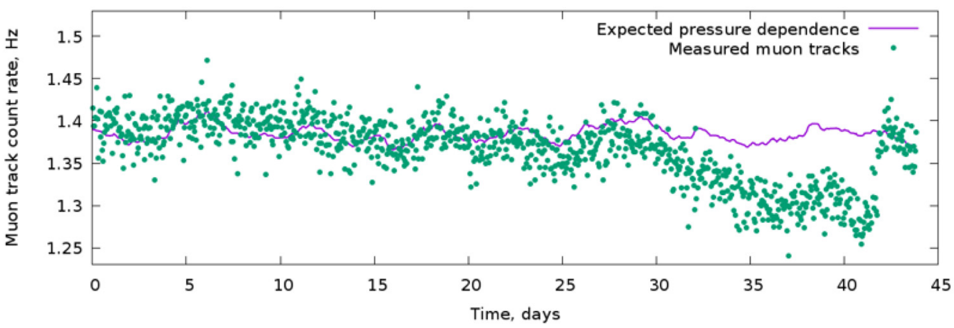

FIG. 4. The track rate time evolution at the open casing test. The gas flow was restored on the 42nd day.

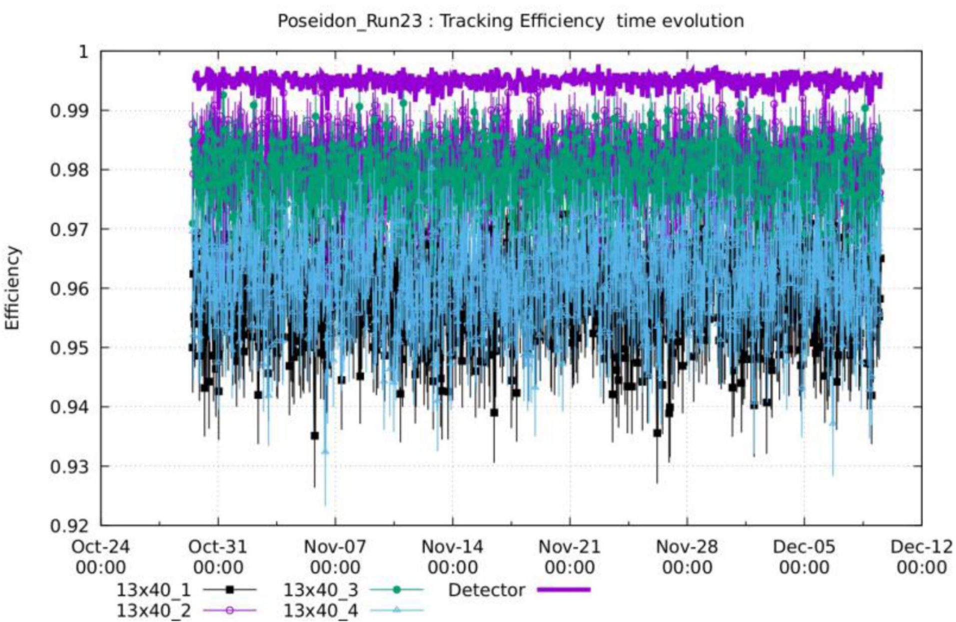

FIG. 5. The tracking efficiency time evolution in sealed mode in the first six week period.

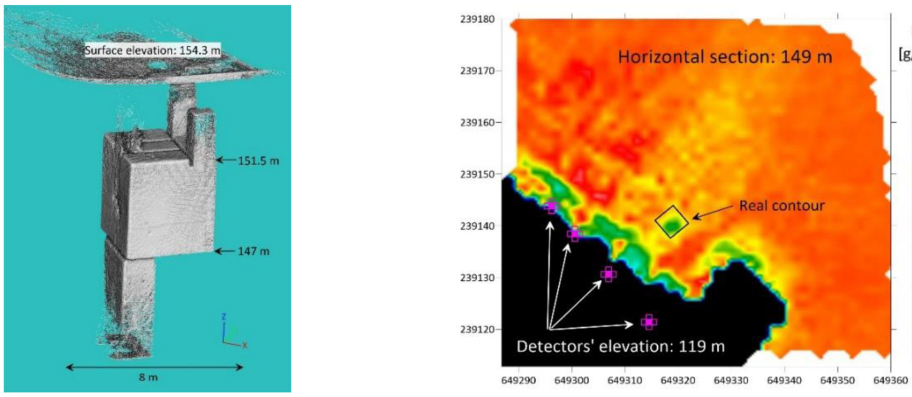

FIG. 6. The model of the void (left) and one of the horizontal sections of the inversion (right).

an alternative if the measurement points are in line (e.g., in a mine tunnel).

Another important improvement was the development of a smartphone application to enable the use of the phone as a remote control for the detectors. As our field measurement activity has increased, more and more people have been involved in detector control and data handling, many of them with no previous knowledge of this type of instrumentation. Using this application, all of our operating detectors can be controlled via a Wi-Fi connection, and the use of the app is very straightforward. The operator can start and stop the measurements, download the data from the device and upload it to our server just by pushing a few buttons. This has made the instrument control and data flow much more efficient.

RESULTS OF SOME CURRENT FIELD MEASUREMENTS

One of our major underground measurement campaigns was the Buda Castle project, where more than a hundred measurements were made from roughly 40 points in order to find unknown voids in the area. This measurement campaign also served as a test site, so the number of detectors involved in this project was also unusually large—altogether, 10 different detectors were used. The detailed analysis of the huge amount of data collected is still ongoing, and many promising targets have been identified. However, one of the most important tasks is to prove the capability of the method and the technology. In order to verify our data processing method, a 3D inversion was carried out using four measurements under a known void. The detectors were placed about 35 m below the surface in a tunnel. The known void, a service shaft of the central heating system, was about 5 m below the surface. All the detectors were on one side of the void, so the geometry for a 3D inversion was far from ideal, as this is the situation in most cases at underground measurements. Despite the unfavorable geometry, the inversion was able to locate the void with very high precision (Fig. 6).

The density values calculated for the void seem to be unrealistic at first sight; however, the distortion is a natural consequence of the Bayesian inversion, and in these geometric conditions,

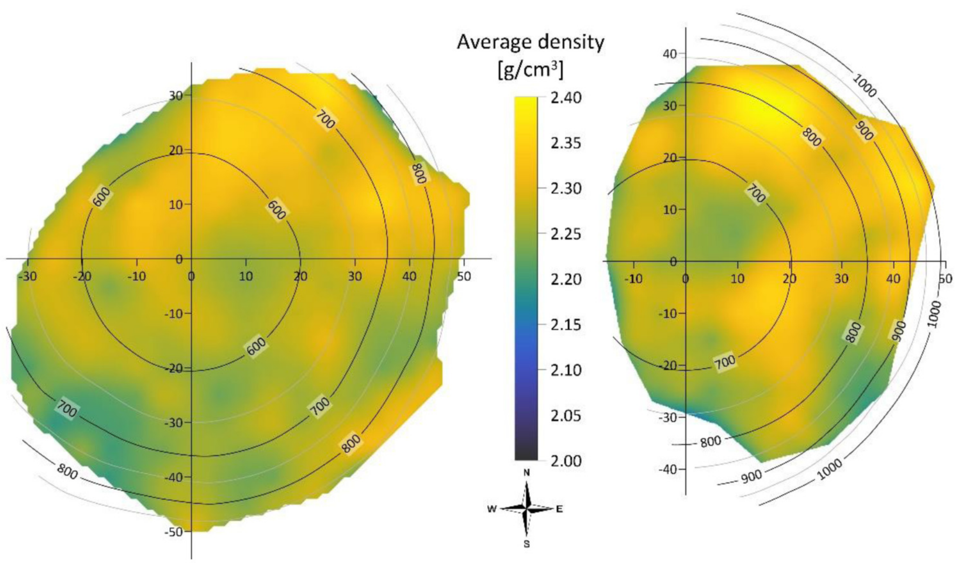

FIG. 7. The measured average density polar plots for the two measurement points. The contour lines indicate the detector-to-surface distances. The average densities calculated by the core drilling information are 2.2–2.3 g/cm^3, depending on the different directions. The areas with insufficient track number for proper flux calculation are blanked.

FIG. 8. The surface detector in a container (left) and the underground detector in the dewatering tunnel (right).

calculating the real zero density for a void would be unrealistic. However, knowing the local geological situation, in this homogeneous rock a significant density anomaly cannot be anything other than a void, so we can state that our method is able to locate any unknown void—larger than $2 \times 2 \times 2\,\mathrm{m}^3$ with similar geometrical conditions—in this area.

Measuring in an active mine is always very challenging, but this was especially difficult in the Lubin copper mine, as mentioned in the "Hardware development" section. However, the result of our measurement campaign is very valuable, as there are very few similar measurements that have been performed deep underground. Our detector was deployed at two measurement points, at vertical depths of 560 and 660 m, respectively. The detector was in a tilted position at both points, so after gathering data for several months we were able to acquire useful data up to 45° zenith angle. The flux data were converted to density-lengths, and by dividing the density-lengths by the detector-to-surface distances, the directional average densities could be calculated (Fig. 7). At this depth, the flux to density-length conversion is not straightforward, because there are differences up to 20% among the results given by different models. Thanks to the numerous boreholes at the area, the sequence of the sedimentary layers above the mine is well-known; thus, the average density values could be calculated for different zenith angles. By comparing the densities obtained by prior geological knowledge to the densities obtained by muon flux measurement, the different flux-to-density-length conversion formulas can be tested. The comparison of different models showed that the Guan parametrization[21] based on the standard Gaisser's formula[22] fits well with our data at this depth for the whole measured zenith angle range.

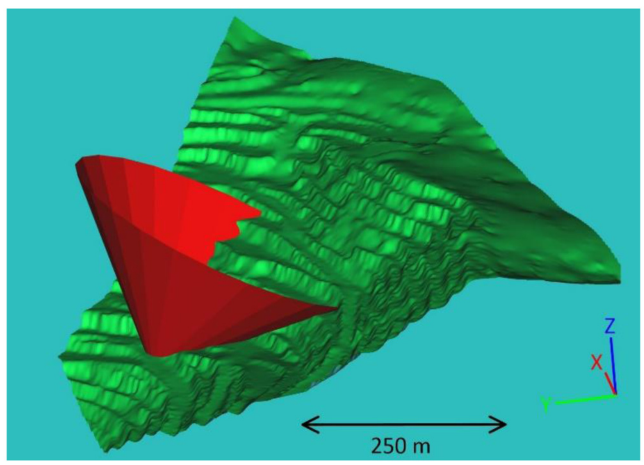

FIG. 9. The part of the open pit mine with the viewing cone of the underground detector. The detector can gather information from the rock body inside the cone.

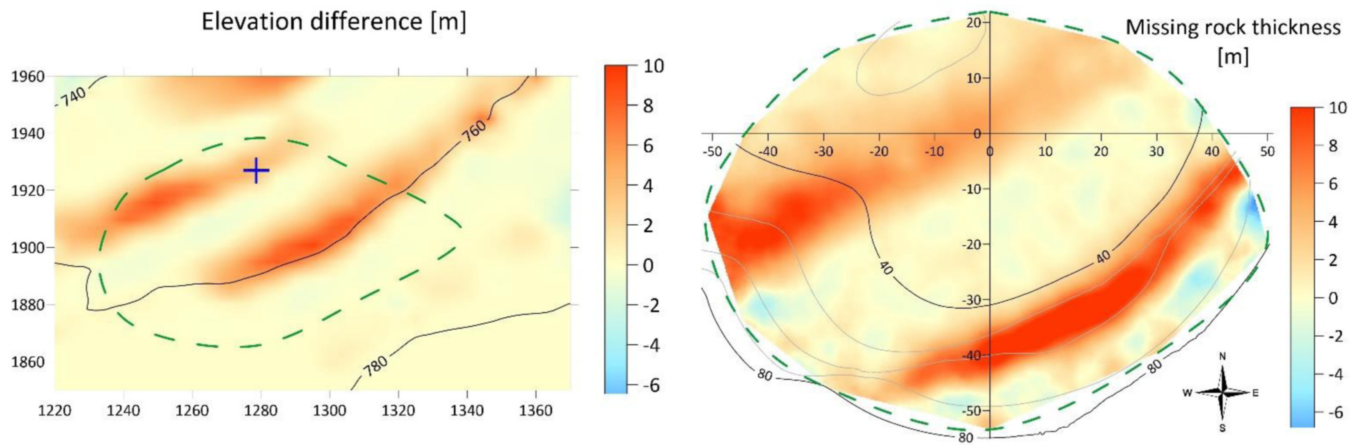

FIG. 10. *Left*: The topography difference obtained by surveying in one month in a Cartesian coordinate system. The contour lines show the elevation at the end of the period. The position of the detector is indicated by blue "+." *Right*: The rock length differences obtained by muography in a polar coordinate system. The contour lines indicate the detector-to-surface distances. The green dashed lines indicate the same area on the surface for easier comparison.

Another challenging place is an open pit mine in Assarel, Bulgaria, where the original goal was to locate a fault zone between the granitoid host rock and the volcanic intrusion. Despite being an open pit mine, there is an old dewatering tunnel that is available for the muography measurement, so both a surface and an underground detector (Fig. 8) were deployed. The surface detector has six MWPC type layers with an $80 \times 80\,\text{cm}^2$ active area, while the underground detector has eight layers with a $50 \times 50\,\text{cm}^2$ active area. The underground detector has a similar stainless-steel casing as the detector mentioned in the previous section. It is an important technical achievement that the underground detector, thanks to the casing, was able to continue operating for one month after it had run out of gas.

The task is especially complex, as the mine is under continuous operation, and the surface in the viewing angle of the detectors is regularly changing as the mine produces different levels of the pit (Fig. 9).

The measurement period was terminated in April 2025. Although the detailed data analysis is still ongoing at the time of writing this article, it can be demonstrated that this continuous changing of the surface allows us to make a 4D muography. This is especially impressive on the underground detector data. Figure 10 shows the changing of the surface based on the mine survey, as well as the difference in the rock lengths based on the muon flux measurements taken one month apart. The two calculations produced similar results in both location and volume of rock removed.

To reach the original goal will be much more difficult in these circumstances; however, the possibility of monitoring of the continuously changing surface opens new fields of application for muography.

CONCLUSION

Continuous development in both hardware and software allows the HUN-REN Wigner RCP to remain at the forefront of muography. Our fieldwork activity is also very significant; presently, we are measuring in five countries in more than ten different projects. We plan to further broaden the scope of our activities and continue pioneering in projects and areas that have previously been unexplored.

ACKNOWLEDGMENTS

This work was supported by the Hungarian NKFIH Research Grant under Identification No. TKP2021-NKTA-10, the HUN-REN Welcome Home and Foreign Researcher Recruitment Programme (KSZF-144/2023), and the "Mine.io" HEU Project (GA No. 101091885). Detector construction and testing was completed within the Vesztergombi Laboratory for High Energy Physics (VLAB) at Wigner RCP. The technical support provided by the members of the REGARD group is gratefully acknowledged.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Gergely Surányi: Conceptualization (equal); Data curation (equal); Writing – original draft (equal). **Dezső Varga:** Supervision (equal); Validation (equal). **Gergő Hamar:** Software (equal); Validation (equal). **Gábor Nyitrai:** Data curation (equal); Software (equal). **László Balázs:** Data curation (equal); Methodology (equal); Software (equal). **Boglárka Stefán:** Software (equal). **Bence Rábóczki:** Data curation (equal); Software (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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