



Real-time monitoring of solar energetic particles outside the ISS with the AMS-02 instrument

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Abstract

Space human activities in the International Space Station (ISS) are always ongoing. The atmosphere and geomagnetic field in this environment only offer partial protection from radiation. Considering the whole energetic spectrum of cosmic rays (CR), the highest energy particles are the most dangerous, but the rarest: on the other hand, sporadic solar emissions of plasma, in the low end of the energetic spectrum, inject an intense and dangerous flux of charged particles called Solar Energetic Particles (SEPs) in the Sun-Earth environment. The experiment Alpha Magnetic Spectrometer (AMS-02) operates on the ISS since 2011, performing precision measurements of cosmic ray composition and flux. In this study we aim to verify if the low latency information provided by AMS-02 could be used to perform SEP and solar activity real-time monitoring in the ISS external environment. An algorithm has been developed to identify sudden increases in the AMS-02 trigger rate with respect to the quiet conditions, demonstrating the potency of AMS-02 low-latency data for this real-time application.

Keywords Cosmic rays · Solar energetic particles · Space weather Heliosphere

1 Introduction

The Sun is a powerful source of energetic charged radiation. Intense bursts of SEPs are emitted during violent events that take place on its surface (Desai and Giacalone 2016). These events are sporadic, but the frequency of their occurrence is

related to the 11-year quasiperiodical cycle of solar activity. The solar cycle alternates epochs of solar maxima and solar minima (Hathaway 2015). Solar maximum is the most active period in terms of SEP occurrences, even though SEP events can occur at any time during the solar cycle, while solar minimum is when the Sun is quiescent. Magnetic reconnection phenomena can cause the release of giant bubbles of coronal plasma, called coronal mass ejection (CME) (Zhang 2021). Usually associated with CMEs, solar flares are intense localized eruptions of electromagnetic and charged radiation in the Sun's atmosphere. During these phenomena, the magnetic energy in the Sun's atmosphere provides acceleration of charged particles up to GeV energies. SEPs are related to CMEs, although many SEP events did not show any CME counterpart, while other phenomena like filament eruptions can cause CMEs without SEPs. Once ejected in the surrounding environment, SEPs propagate through interplanetary space and may reach the Earth. They are capable of damaging instruments onboard satellites and represent a primary risk for crewed space missions (Durante and Cucinotta 2014). In this paper, we present the SEP ID algorithm's main results, showing the SEP events successfully identified by this approach and describing the difficulty of detecting solar particles of rigidity near the geomagnetic cutoff regions of Earth.

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2 Ionizing radiation in space

Radiation hazards is a prime concern in space missions. Spacecrafts are constantly exposed to intense ionizing radiation, which is detrimental to human health and to the equipment. Space radiation may place astronauts at significant risk for radiation sickness, increased risk for carcinogenesis, central nervous system effects, and degenerative diseases (Cucinotta and Durante 2006). Cosmic Rays have a Galactic component and Solar one. Galactic Cosmic Rays (GCR) constitute the primary radiative exposure during the solar minimum, because of the lower shielding by the solar magnetic field, and are isotropic. SEPs represent the sporadic emission of higher energy particles in the solar component and are not isotropic. Another relevant characteristic is the short-term variation of SEPs (hourly), while the Galactic component is subjected to a longer variation, following to the solar activity cycle. The radiation environment of the International Space Station (ISS) is studied by various experiments such as DOSIS-3D (Berger 2016), LIDAL (Rizzo 2018), or wearable dosimeters. All these instruments are placed inside the ISS modules. Monitoring radiation outside the ISS could be useful for the planning of extravehicular activities, crewed missions in the low-Earth orbit, or for dedicated studies on radiation shielding. An external monitoring system could also provide a direct measurement of the absorbed dose outside the shielding of the ISS modules, monitoring the actual health conditions of the crew. The Alpha Magnetic Spectrometer (AMS-02) experiment is well suited to carry out these activities.

3 The AMS-02 experiment

AMS-02 is a high-energy physics detector operating as an external module on the ISS since May 2011. The experiment will be maintained until the end of the ISS program (Kirn 2013). The AMS-02 experiment takes advantage of the environment of the low-Earth orbit to operate direct measurements of cosmic rays outside the atmosphere. It is constituted by several sub-detectors. The time-of-flight (TOF) system is made of four segmented scintillator planes placed above and below the spectrometer. It measures the particle velocities, their incoming directions and their charge. The silicon tracker, made of nine layers of silicon microstrip detectors, measures the bending of the particle trajectories inside a cylindrical permanent magnet. This leads to the determination of particle momentum and charge sign. The magnet is aligned with an Anti-Coincidence system (ACC) made of scintillators, to provide

a veto signal for multi-particle events. The Transition Radiation Detector provides the CR lepton/hadron separation. The Ring Imaging Cherenkov detector provides measurements on velocity and charge. The 3D-imaging Electromagnetic Calorimeter (ECAL) is used to measure the total energy of electrons and to improve the leptons/hadron separation.

The AMS-02 experiment is devoted to the precision measurement of CR fluxes at GeV-TeV energies and the search of CR antimatter. AMS-02 is also capable of monitoring the time dependence of the CR flux in terms of intensity and composition over a long-term measurement campaign which has achieved a duration of at least one solar cycle. Precision measurements of the time dependence of the flux of CRs have been already published by AMS-02 (Aguilar 2018a, b, 2021a, b).

4 Analysis

AMS-02 provides accurate measurements on charge, energy, and time resolved fluxes of CRs (Aguilar 2021c). The analysis discussed here, however, is based on low-level and low-latency data on the trigger rate, which is well suited for the purpose of near-real-time measurements and alarms. The trigger signal of the experiment is provided by the sub-detectors TOF, ACC and ECAL. This signal is responsible for the data taking (DAQ) relative to each interesting event. Seven different types of trigger signal exist: five of them are called “physical” and associate the single event to the detection of different particles (proton, electron, normal ion, fast ion and photon). The remaining two “non physical” trigger signals, which expect less conditions than physical ones, are prescaled with a factor of 100. In this work, we used the total trigger rate, comprehensive of all the seven trigger signals. The rate of particles that trigger the AMS-02 DAQ system (i.e. trigger rate) depends on the position and orientation of the ISS in the local geomagnetic field. In Fig. 1, the dependence of the AMS-02 trigger rate on geographical coordinates of the ISS is shown, cumulated over the periods when AMS-02 operated in nominal conditions. The average trigger rate is about 700 Hz, ranging from ~ 200 Hz near the equators to ~ 1200 Hz in the polar regions. The trigger rate is significantly suppressed when the AMS-02 crosses the South Atlantic Anomaly (SAA), due to the lowering of DAQ efficiency by the large increase of low energy particles crossing the detector.

4.1 Rigidity cutoff

SEPs can reach GeV energies, but their flux usually peaks at 10–100 MeV of kinetic energy (Klein and Dalla 2017), i.e., below the AMS-02 detection threshold. Also, AMS-02

Fig. 1 AMS-02 total trigger rate density in geographical coordinates: magnetic polar regions show high trigger rates due to low rigidity cutoff conditions. The SAA boundary is visible, within which the livetime drops significantly

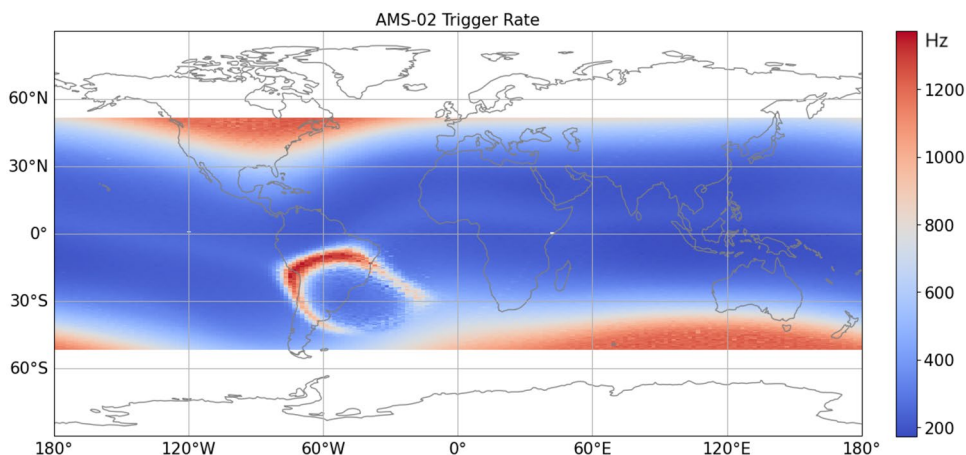
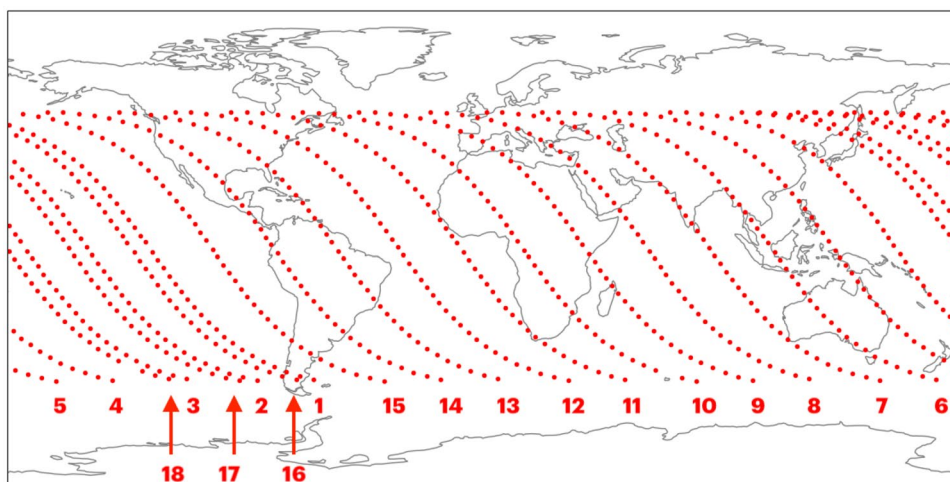


Fig. 2 Orbital daylight tracks for 18 consecutive orbits of the ISS. The ISS is subjected to a precession of 22.9° per complete orbit, in the opposite direction of its motion. Each point represents a sampling of the ISS trajectory every minute



experiment is blind to CR particles below the rigidity cutoff R_c , as they are unable to penetrate the Earth’s magnetic field (Smart 2005). A useful parametric formula for the geomagnetic cutoff R_c is the Störmer formula:

$$R_c = \frac{M_E}{r^2} \frac{\cos^4 \Theta_{mag}}{\left[1 + \sqrt{1 - Q \cdot \sin \theta \cdot \sin \phi \cdot \cos^3 \Theta_{mag}} \right]^2} \quad (1)$$

where Q is the particle charge, θ and ϕ are the polar and azimuthal angles of the particle with respect to the local zenith, Θ_{mag} is the geomagnetic latitude and M_E is the Earth’s magnetic moment.

4.2 Orbital precession

The ISS orbit has 51.6° of inclination, an altitude of 330–410 km from the sea level, and an orbital period is about 91 min. At every orbit the ISS is subjected to a westward precession of 22.9° of geographic longitude. After a complete Earth’s rotation (1 day, 15.7 orbits), the

ISS retraces the same coordinates, with a phase shift with respect to the previous cycle. This is illustrated in Fig. 2. In this work, we call *Orbital Precession Period* (OPP) the time after which the equator crossing of the ISS shifts by 360° in azimuthal angle.

The ISS precession plays an important role in SEP detection with AMS-02. In fact, due to the shielding of the geomagnetic field, the AMS-02 sensitivity to SEPs is limited to the low- R_c regions, *i.e.*, the high-latitude regions within a given range of longitudes.

4.3 SEP identification algorithm

Here, we describe our algorithm for the identification of SEP occurrences with the AMS-02 data on the trigger rate. The key parameters are: total trigger rate, Unix Time, DAQ livetime, ISS position, ISS orientation, and maximum IGRF cutoff (Alken 2021). The latter is the maximum value of the geomagnetic cutoff R_c calculated from the IGRF model for particles reaching AMS-02 within a 25° field-of-view around the zenith direction. A further selection is made to

Table 1 In this table is reported the number of “true” and “false” SEP events registered by the algorithm in each year, for different significance threshold values

S threshold	2011	2012	2013	2014	2015	2016	2017	Total
5	2–1	8–1	4–4	5–2	1–4	0–10	2–7	22–29
6	2–0	6–1	4–2	4–0	1–1	0–4	1–7	18–15
7	2–0	6–0	4–1	4–0	1–0	0–0	1–3	18–4
SESC events	6	13	8	5	2	1	2	37

On the last row is reported the number of SEP events found in the SESC database described in Section 5. The “true” events found on AMS data (left number in each cell) are also found in the SESC database, while “false” events (right number) are not

reject events that do not meet the DAQ quality requirements, or collected when the ISS was passing through the SAA. The SEP ID algorithm is mostly based on the time-averaged trigger rates, normalized by the relevant livetime fraction. The normalization accounts for the loss of trigger events. The average livetime fraction is $\geq 90\%$ but it gets reduced when the trigger rate increases.

A dynamic evaluation of the solar quiet level is essential to determine the occurrence of a SEP-induced excess in the trigger rate. Even in quiet solar period, the trigger rate is subjected to short-term variations (at sub-daily scales) related to the ISS orbit and to long-term variation (at monthly scales) related to the solar activity cycle (Aguilar 2018c, 2021a). The SEP ID algorithm developed in this work was designed to tackle such a limitation, with a definition of a time-dependent reference threshold. To minimize fluctuations in the trigger rate data, each cumulative parameter was integrated in 1-min time intervals. For each interval, the mean trigger rate and its standard deviation were calculated considering all values of the trigger rate in the previous 5 OPP. Moreover, their calculations were done for N different intervals of rigidity cutoff; these values were then stored into N -dimensional arrays. Trigger rates above threshold, corresponding to a given solar activity interval, were not considered for the calculation of the quiet level. The use of 5 OPP/day period is related to the maximum duration of SEP events and may be subjected to further optimization.

The logic of the the SEP ID algorithm is illustrated in Fig. 3. The algorithm is fed by all the data (trigger rate $R_{tr}(i)$, livetime $lvt(i)$, cutoff value $cutoff(i)$, ecc.). For the i -th data point, it determines the corresponding cutoff interval $\beta(i)$. Then, the mean $\mu(i)$ and standard deviation $\sigma(i)$ of the trigger rate measured in similar geomagnetic conditions (i.e., in the same cutoff rigidity interval) over the 5 last occurring OPP are calculated. With this information, along with the trigger rate $R_{tr}(i)$, the *significance score* $S(i)$ is evaluated:

$$S(i) = \frac{R_{tr}(i) - \mu(i)}{\sigma(i)} \tag{2}$$

The S -score measures to which extent each data point is related to a significant disturbance. The start of a potential SEP event is defined by the criterion $S \geq 7$, met by three consecutive data points. The decision of defining a significance threshold equal to 7 is based on the evidence that, selecting a different threshold, we would register either an excess of false events or a loss of true ones, as it can be seen in Table 1. Events with less than three consecutive data points are discarded. Events with $S < 7$ are used to evaluate the quiet level. Candidate SEP events are stored in a separate array.

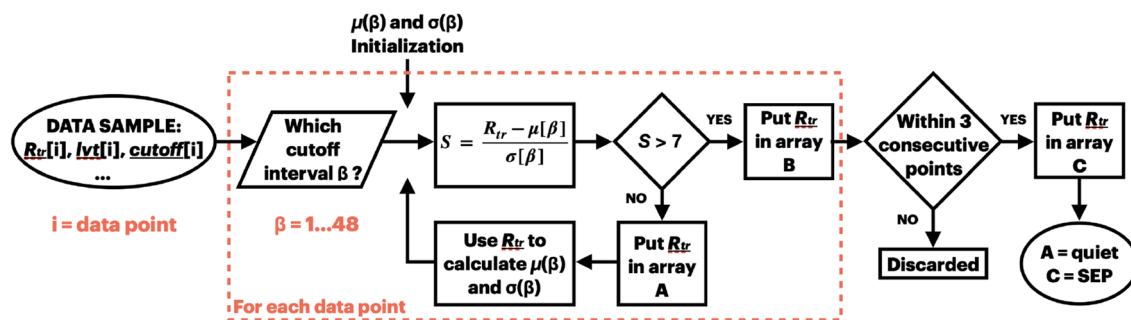


Fig. 3 The SEP Identification Algorithm. The algorithm determines whether each time interval under analysis is part of a SEP event, based on the analysis of the historical data taking state of AMS-02 in similar geomagnetic conditions for the five last precession orbits

Fig. 4 Proton flux (10 MeV) with respect to time for 2012 using GOES data (GOES proton GOES proton). The NOAA database threshold (Solar Solar) is represented by the horizontal line (flux > 10 pfu). The flux with significance $S > 7$ from quiet level, found by this algorithm, is represented by colored blue dots

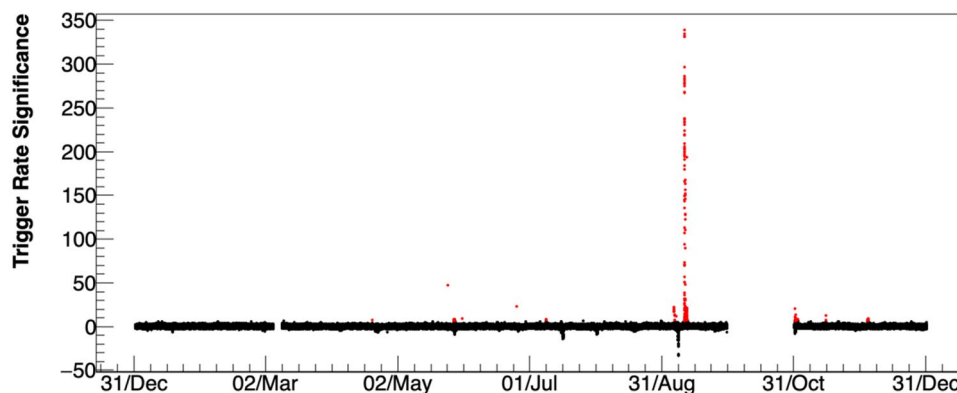
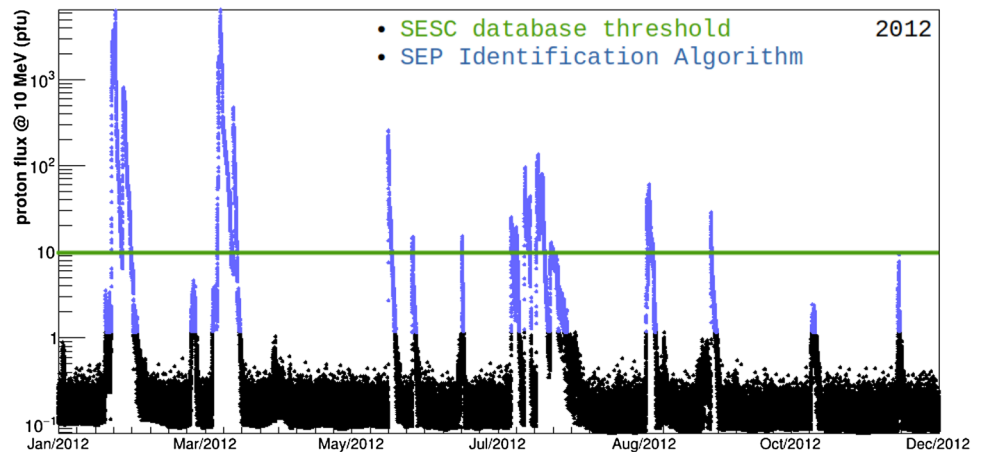


Fig. 5 Significance value with respect to time for 2017 on AMS-02 data. The red dots represent one-minute intervals in which the trigger rate was above significance threshold, as described in Sect. 4.3. Intervals with less than three consecutive dots, as well as false events, are

shown here, but discarded by the algorithm when creating the list of SEP events. The event of September is one of the most prominent in recent history and it is clearly visible in this plot

5 Results and discussion

The application of the SEP ID algorithm, developed in the context of this work and applied on AMS-02 data from 19/05/2011 to 31/12/2018, has identified a set of SEP candidate events. Our results have been compared with other publicly available data. For instance, the NOAA Space Environment Service Center (SESC) provides a detailed SEP proton events listing based on the data from GOES satellites at Geosynchronous orbit (GOES proton <https://www.swpc.noaa.gov/products/goesproton-flux>; Solar <https://umbra.nascom.nasa.gov/SEP/>). In the GOES data, the CR proton flux is integrated over 5 min for energies above 10 MeV, in Particle Flux Units (*pfu*), where $1 \text{ pfu} = 1 \text{ particle cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$. In this database, the beginning (ending) of a SEP is defined by the first (last) 3 consecutive data points having flux larger than 10 *pfu*. The algorithm developed in this work was also applied

to the GOES data, using the same threshold $S \geq 7$. For the GOES geostationary orbit (at altitude 42,164 km), the geomagnetic cutoff modulation is always negligible. The results are shown in Fig. 4 for the GOES data in the year 2012. It can be seen that the SEP ID Algorithm recovers all the SESC events. It also finds minor events below SESC threshold.

A similar plot on AMS-02 data is pictured in Fig. 5, where the significance value S is shown with respect to time for the whole 2017. Since the analysis is based on AMS-02 preliminary data, it has not been possible to show directly the trigger rate from the instrument.

The SEP candidate events found by our algorithm applied to AMS-02 and GOES data are listed in Table 2 and compared with the SESC events. With AMS-02, the major SEP events are successfully identified, while several low-intensity events appear not to give a significant contribution to the AMS-02 trigger rate. A possible interpretation is that, for short-lived events, AMS-02 has small chances to be within

Table 2 Major 2012 SEP events, i.e. events with the highest proton flux and trigger rate, identified by the SEP Identification Algorithm on AMS-02 data developed in this work

SESC		SEP ID Algorithm on AMS-02		SEP ID Algorithm on GOES	
Start	Max flux (pfu)	Start	Max trigger rate (Hz)	Start	Max flux (pfu)
Jan 23	6310	Jan 23	4453	Jan 22	6310
Jan 27	796	Same event	Same event	Same event	Same event
Mar 07	6530	Mar 07	110,893	Mar 05	6350
Mar 13	469	Mar 13	3234	Same event	Same event
May 17	255	May 17	5111	May 17	255
May 27	14			May 27	14.8
Jun 16	14			Jun 16	14.9
Jul 07	25	Jul 08	1963	Jul 07	25.2
Jul 12	96			Jul 12	96.1
Jul 17	136			Jul 17	136
Jul 23	12			Same	Same
Sep 01	59			Sep 01	59.9
Sep 28	28			Sep 28	28.4
				Nov 09	2.4
				Dec 14	9.4

All the events reported in the SESC listing are also found by the algorithm on GOES data for comparison. See text for a discussion of the results

polar regions, where the rigidity cutoff is minimum, at the time in which the peak energy of SEPs is above detecting threshold. Between each polar crossing of the ISS there is, in fact, a period of about 8 h in which AMS-02 is not sensitive at all to SEPs. Furthermore, if we are interested in the safety of the ISS radiation environment, SEP events not detected by AMS-02 do not constitute a major concern for operations in low-Earth-orbit environment, as AMS-02 is located in the same radiation conditions of the ISS. On the other hand, high-energy SEPs must be shielded by the ISS hull, hence the importance of having a monitoring systems in the ISS.

6 Conclusions

In this paper, we have demonstrated that the low-latency data of the AMS-02 detector could be exploited to provide a service for real-time monitoring of CR radiation for the low-Earth orbit environment. In particular, we focused on the identification of solar events. The algorithm has been applied to provide results on AMS-02 trigger data from 19/05/2011 to 31/12/2018. The same algorithm has been validated by its application on GOES data collected in the same period. The comparison between the SEP candidates identified by the algorithm developed in this work and applied separately on AMS-02 and GOES data, and compared on existing compilation of SEP events occurred between 2011 and 2019 has provided evidence that AMS-02 can identify intense SEP events when the maximum energy is above the AMS-02 trigger quiet level threshold. This provides evidence that the AMS-02 detector can contribute with precious information

on the radiation level outside the ISS vessel, especially for high intense SEP events that can represent health and operation hazards during space operations.

In conclusion, our results suggest that the application of AMS-02 low-latency data for a real-time analysis could be a valid option to enhance radiation monitoring in the ISS orbit environment.

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Declarations

Conflict of interest The authors report that they have no conflicts of interest. The authors alone are responsible for the content and writing of this article.

Ethical approval All authors have approved this manuscript, agree to the order in which their names are listed and declare that no conflict of interest exists.

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