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Original Article

Small Modular Reactors: An Innovative Proposal for Brazil's Energy Transition

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Abstract: Small Modular Reactors (SMRs) represent a promising technological innovation for energy transition, offering enhanced safety, operational flexibility, and modularity. This study examines critical success factors for SMR implementation in Brazil's energy matrix, addressing regulatory, economic, technical, and social dimensions. A qualitative approach combined bibliometric analysis of 190 documents from Scopus with semi-structured interviews of nine Brazilian experts with over 15 years of experience. Results reveal regulatory framework inadequacy was identified by 77.8% of experts as the primary barrier, followed by capacity building needs (55.6%), risk management challenges (55.6%), and economic viability concerns (44.4%). Private sector participation (66.7%) and diverse industrial applications (33.3%) emerged as key opportunities. SMRs can contribute to decarbonization goals and energy security in Brazil, particularly for industrial applications in petrochemical facilities, mining operations, and offshore platforms. Successful implementation requires: (1) continuous state nuclear policy; (2) SMR-specific regulatory frameworks; (3) public-private partnership models; (4) capacity building programs; and (5) transparent communication strategies. This research provides empirical evidence from Brazilian experts and specific recommendations for policymakers, regulators, and industry stakeholders.

Keywords: small modular reactors; energy transition; nuclear energy; Brazil; regulatory framework; decarbonization.

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Reatores Modulares Pequenos: Uma Proposta Inovadora para a Transição Energética do Brasil

Resumo: Os Reatores Modulares Pequenos (SMRs) representam uma inovação tecnológica promissora para a transição energética, oferecendo maior segurança, flexibilidade operacional e modularidade. Este estudo examina os fatores críticos de sucesso para a implementação de SMRs na matriz energética brasileira, abordando dimensões regulatórias, econômicas, técnicas e sociais. Uma abordagem qualitativa foi adotada, combinando análise bibliométrica de 190 documentos da base Scopus com entrevistas semiestruturadas realizadas com nove especialistas brasileiros com mais de 15 anos de experiência. Os resultados revelam que a inadequação do arcabouço regulatório foi identificada por 77,8% dos especialistas como a principal barreira, seguida pela necessidade de capacitação (55,6%), desafios na gestão de riscos (55,6%) e preocupações com a viabilidade econômica (44,4%). A participação do setor privado (66,7%) e a diversidade de aplicações industriais (33,3%) emergem como oportunidades-chave. Os SMRs podem contribuir para os objetivos de descarbonização e para a segurança energética no Brasil, especialmente em aplicações industriais como instalações petroquímicas, operações de mineração e plataformas offshore. A implementação bem-sucedida requer: (1) uma política nuclear de Estado contínua; (2) marcos regulatórios específicos para SMRs; (3) modelos de parceria público-privada; (4) programas de capacitação; e (5) estratégias de comunicação transparentes. Esta pesquisa fornece evidências empíricas baseadas na percepção de especialistas brasileiros e apresenta recomendações específicas para formuladores de políticas públicas, órgãos reguladores e atores do setor industrial.

Palavras-chave: reatores modulares pequenos; transição energética; energia nuclear; Brasil; marco regulatório; descarbonização.

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1. INTRODUCTION

The global energy transition toward low-carbon sources has intensified the search for reliable and sustainable technologies capable of supporting decarbonization goals and long-term energy security. In this context, nuclear energy has regained strategic relevance due to its low greenhouse gas emissions and firm electricity generation capacity [1].

Small Modular Reactors (SMRs), defined as nuclear reactors with electrical capacity up to 300 MWe per module, represent an emerging technological alternative characterized by modular construction, operational flexibility, and enhanced passive safety systems [2]. SMRs also present potential industrial and non-electric applications [3].

Brazil possesses one of the world's cleanest electricity matrices, predominantly based on renewable sources. Nevertheless, challenges associated with energy security, industrial decarbonization, and the intermittency of renewable generation reinforce the importance of evaluating complementary low-carbon technologies capable of supporting long-term energy planning [4], [5].

Despite technological advances, SMR deployment still faces important barriers related to regulatory adaptation, financing mechanisms, institutional governance, workforce qualification, and public acceptance. These challenges are particularly relevant in Brazil, where the regulatory framework was originally developed for large conventional reactors.

This study addresses the following research question: What are the critical success factors for SMR implementation in Brazil's energy matrix? The objective is to identify and analyze facilitating and hindering factors associated with SMR deployment in Brazil across regulatory, economic, technical, and social dimensions.

This research contributes by combining bibliometric analysis and expert interviews to provide empirical evidence regarding the opportunities and challenges associated with SMRs in the Brazilian energy transition context.

2. THEORETICAL FRAMEWORK

2.1. Small Modular Reactors: Technological Innovation

SMRs are advanced nuclear reactors with electrical capacity up to 300 MWe per module, designed for modular deployment and factory fabrication [2]. Their main characteristics include passive safety systems, operational flexibility, modular construction, and reduced upfront capital requirements compared with conventional large reactors. SMRs may support electricity generation as well as industrial applications such as hydrogen production, desalination, and process heat supply [3].

2.2. Energy Transition and Decarbonization

Energy transition involves the gradual replacement of fossil fuels by low-carbon energy sources. In this context, nuclear energy may contribute to decarbonization and energy security by providing firm electricity generation complementary to renewable sources [1].

2.3. Institutional Theory and Technology Adoption

Institutional theory emphasizes the importance of regulatory frameworks, governance structures, and public policies in technological development and adoption [6]. Rogers' Diffusion of Innovations theory highlights how institutional, economic, and social factors influence the acceptance of emerging technologies [7].

2.4. Critical Success Factors

Literature identifies regulatory and institutional, economic and financial, technical and technological, and social acceptance and communication dimensions as critical factors influencing SMR deployment and public acceptance in Brazil.

3. METHODOLOGY

3.1. Research Design

This study adopted an exploratory qualitative approach combining bibliometric analysis and semi-structured expert interviews to identify critical success factors for Small Modular Reactor (SMR) implementation in Brazil's energy transition context. The methodological design sought to integrate evidence from international scientific literature with the perceptions and professional experience of Brazilian specialists involved in nuclear energy, regulation, planning, and research activities. The integration between bibliometric analysis and interviews enabled triangulation between trends identified in the international literature and the critical factors highlighted by experts in the Brazilian context. [8].

3.2. Bibliometric Analysis

A bibliometric review was conducted using the Scopus database to identify the main scientific narratives, thematic trends, and international discussions regarding SMRs, energy transition, decarbonization, governance, and nuclear regulation. The search strategy included combinations of the following descriptors: ("small modular reactor" OR "SMR") AND ("energy transition" OR "decarbonization" OR "nuclear energy" OR "regulatory framework" OR "Brazil").

The inclusion criteria considered peer-reviewed journal articles, conference papers, books, and technical reports published between 2014 and 2024 in English or Portuguese.

Duplicates and publications unrelated to energy transition or SMR applications were excluded. The final dataset comprised 190 documents.

The bibliometric stage aimed not only to characterize the evolution of scientific production but also to support the construction of the interview protocol. The thematic categories identified in the literature review — including regulatory barriers, economic feasibility, technological readiness, public perception, governance, capacity building, and industrial applications — were subsequently incorporated into the semi-structured interview script. This articulation between bibliometric findings and interviews ensured methodological coherence between both stages of the research.

3.3. Expert Interviews

Semi-structured interviews were conducted with nine Brazilian experts (E1–E9) selected through purposive sampling based on their recognized experience in nuclear energy, regulation, academia, research institutions, and energy policy. All participants possessed more than 15 years of professional experience in the nuclear sector and represented institutions including CNEN, Eletronuclear, IEN, IPEN, UFRJ, and UFF.

The interviews were conducted between January and February 2025, lasted approximately 60–90 minutes, and were recorded with participant consent and later transcribed for analysis. A common semi-structured interview protocol was adopted for all participants to ensure consistency and comparability among responses. However, flexibility was maintained to allow interviewees to expand upon issues considered particularly relevant according to their professional expertise and experience.

The interview script was developed based on the literature review and bibliometric analysis results and addressed topics such as: barriers to SMR implementation in Brazil; regulatory and institutional challenges; economic feasibility and financing mechanisms; technological readiness and infrastructure; public acceptance and communication; opportunities for industrial and non-electric applications; governance and energy policy perspectives.

Participants were not provided with predefined answer categories or lists of expected factors before the interviews. Instead, open-ended questions were used to stimulate spontaneous expert assessments and encourage the identification of relevant facilitating and hindering factors associated with SMR deployment in Brazil.

3.4. Critical Incident Technique

The Critical Incident Technique (CIT), proposed by Flanagan [9], was adapted in this research as a qualitative analytical strategy to identify situations, conditions, and factors perceived by experts as critical for the successful or unsuccessful implementation of SMRs in Brazil. Unlike classical applications of CIT focused exclusively on personally experienced operational events, this study employed the technique in an expert-assessment context.

Thus, interviewees were invited to describe concrete examples, institutional experiences, regulatory situations, policy failures, technological constraints, or international reference cases that they considered particularly significant for facilitating or hindering SMR deployment. The objective was not to collect autobiographical incidents alone, but rather to identify expert-recognized critical conditions capable of influencing decision-making, governance, licensing, investment attractiveness, and social acceptance.

Based on reference [8], the incidents and expert statements were subsequently classified into four analytical dimensions: regulatory and institutional factors; economic and financial factors; technical and technological factors; social acceptance and communication factors.

This adaptation of CIT proved appropriate for examining complex emerging technologies, such as SMRs, in which expert judgment and institutional experience constitute important sources of evidence for understanding implementation challenges and opportunities.

3.5. Data Analysis

The interview transcripts were analyzed using thematic content analysis supported by NVivo software. Coding procedures were conducted iteratively to identify recurring themes, patterns, and relationships among the responses. Categories emerging from interviews were

compared with the themes identified during the bibliometric review, allowing triangulation between literature evidence and expert perceptions.

Frequency analysis was employed to identify the relative prominence of critical factors among experts, while qualitative interpretation enabled deeper examination of the institutional, technological, and governance dimensions associated with SMR deployment in Brazil.

3.6. Ethical Considerations

This research was approved by the Ethics Committee of Universidade Federal Fluminense under Protocol No. 78654424.0.0000.5243. All participants signed informed consent forms prior to the interviews, and confidentiality was preserved through anonymization of participant identities.

4. RESULTS

4.1. Bibliometric Analysis Findings

The bibliometric analysis of 190 documents revealed a significant increase in scientific interest in Small Modular Reactors (SMRs) and advanced nuclear technologies between 2014 and 2024, particularly after 2020. This growth reflects increasing global concerns regarding decarbonization, energy security, and the need for reliable low-carbon energy sources capable of supporting net-zero transition pathways.

The literature highlights SMRs as a promising option for expanding clean energy generation while providing flexibility for non-electric applications, including hydrogen production, district heating, desalination, and industrial process heat. In addition, several studies emphasize the potential contribution of SMRs to remote and isolated regions where conventional large-scale nuclear plants may not be economically viable.

Thematic analysis identified four recurring dimensions associated with SMR deployment: regulatory and institutional frameworks, economic and financing challenges, technical and

technological aspects, and social acceptance and communication strategies. Regulatory adaptation, licensing uncertainty, financing mechanisms, public acceptance, and technological readiness emerged as the most frequently discussed topics across the reviewed publications.

Although the majority of publications originate from countries with established nuclear programs, the literature increasingly recognizes the importance of evaluating national contexts and institutional conditions for successful SMR deployment. These findings provided the analytical foundation for the subsequent examination of expert perceptions

4.2. Integration Between Bibliometric Findings and Expert Interviews

The comparison between bibliometric findings and expert interviews revealed strong convergence regarding the factors influencing SMR deployment in Brazil. Regulatory, economic, technical, and social issues emerged consistently in both sources of evidence, while the interviews provided insights into their specific implications within the Brazilian institutional and energy context.

Additionally, the interviews revealed aspects that are less emphasized in the international literature, including constitutional restrictions associated with nuclear activities, institutional coordination among Brazilian nuclear organizations, and opportunities related to offshore and mining applications. These findings reinforce the relevance of considering national specificities when evaluating future SMR deployment strategies.

4.3. Application of the Critical Incident Technique

The Critical Incident Technique enabled the identification of the main facilitating and hindering factors perceived by specialists as relevant to SMR deployment in Brazil. The incidents reported by interviewees were grouped into four analytical dimensions: regulatory and institutional factors, economic and financial factors, technical and technological factors, and social acceptance and communication factors.

The analysis showed that regulatory and institutional issues represented the most frequently cited barriers, followed by technical capacity-building needs and economic

concerns. At the same time, opportunities associated with private sector participation, industrial applications, and long-term strategic planning were identified as important enabling conditions for future SMR implementation. Table 1 summarizes the most relevant critical incidents identified, while the following subsections discuss the main barriers and opportunities in greater detail.

4.4. Expert-Identified Barriers

4.4.1. Regulatory Framework Inadequacy (77.8%)

Seven experts identified regulatory barriers as the principal obstacle to SMR deployment in Brazil. The issue emerged spontaneously in nearly all interviews, reinforcing the prominence already identified in the bibliometric review. E3 stated: "Current regulations were designed for large reactors. SMRs require specific frameworks addressing modularity, factory fabrication, and different risk profiles." And E7 emphasized: "Licensing timelines are prohibitive. We need streamlined processes for standardized designs while maintaining safety rigor."

The interviews highlighted concerns regarding: absence of SMR specific licensing criteria; lack of regulatory precedents for modular construction; lengthy licensing processes; uncertainty regarding private sector participation; need for international harmonization and cooperation. Future regulatory developments will likely require an active role from ANSN in establishing licensing requirements adapted to SMR technologies in Brazil.

4.4.2. Capacity Building Needs (55.6%)

Five experts emphasized workforce qualification and technological infrastructure as critical conditions for future SMR deployment. E2 observed: "Brazil has nuclear competence from Angra reactors, but SMRs require new skills in modular construction, advanced materials, and digital instrumentation."

The interviews also identified: aging workforce concerns; insufficient specialized university programs; limited industrial supply chain qualification; dependence on international technology transfer.

4.4.3. Risk Management Challenges (55.6%)

Risk management concerns emerged in both technical and institutional dimensions. Experts referred to: first-of-a-kind deployment risks; financing uncertainty; cybersecurity vulnerabilities; radioactive waste management; emergency preparedness for distributed deployment. E4 highlighted: "First-of-a-kind risks are significant. Cost overruns and delays in pioneer projects could undermine SMR credibility."

4.4.4. Economic Viability Concerns (44.4%)

Economic feasibility was associated with: high initial capital costs; uncertainty regarding serial production economies; lack of financing mechanisms; investor risk perception. E6 stated: "Financing is challenging. Banks are risk-averse to nuclear projects. We need innovative models: public-private partnerships and development bank support."

4.5. Expert-Identified Opportunities

4.5.1. Private Sector Participation (66.7%)

Six experts identified private participation as a major opportunity enabled by SMRs due to reduced scale and lower capital requirements compared with conventional large reactors. E9 emphasized: "Industrial consumers—petrochemicals, mining, offshore oil—need reliable, low-carbon energy. SMRs offer compelling value propositions." The interviews highlighted the strategic relevance of: public-private partnerships; industrial self-generation; distributed nuclear applications; low-carbon industrial heat production.

4.5.2. Industrial and Non-Electric Applications (33.3%)

Several experts discussed industrial applications as potential entry points for SMR deployment in Brazil, particularly in petrochemical complexes; mining operations; offshore platforms; hydrogen production and desalination systems.

Table 1 : Critical incidents identified by experts and their classification by analytical dimension

Critical Incident	Frequency (%)	Analytical Dimension
Inadequate regulatory framework for SMRs	77.8	Regulatory and Institutional Factors
Need for public-private partnership models	66.7	Economic and Financial Factors
Risk management and licensing uncertainties	55.6	Regulatory and Institutional Factors
Workforce qualification and training needs	55.6	Technical and Technological Factors
Economic viability and financing challenges	44.4	Economic and Financial Factors
Industrial and non-electric applications	33.3	Technical and Technological Factors
Absence of a long-term State Nuclear Policy	Qualitative evidence	Regulatory and Institutional Factors
Public acceptance and communication strategies	Qualitative evidence	Social Acceptance and Communication Factors

4.6. International Experiences and Comparative Perspectives

Experts frequently referred to international experiences as reference models for Brazil. Canada, the United Kingdom, the United States, and Argentina were repeatedly mentioned due to advances in licensing adaptation, demonstration projects, financing models, and government support mechanisms. E6 commented: "Canada's regulatory approach is exemplary. Brazil should study these models rather than reinventing processes."

5. DISCUSSIONS

5.1. Regulatory Framework as the Main Critical Barrier

The finding that 77.8% of experts identified regulatory inadequacy as the principal barrier to SMR deployment is strongly aligned with the international literature identified in the bibliometric review. The interviews reinforced that Brazil's current regulatory structure was originally developed for large conventional nuclear reactors and does not fully address the characteristics of modular, factory-fabricated, and potentially distributed SMR technologies. The integration between bibliometric findings and expert interviews demonstrated convergence regarding the importance of regulatory predictability, licensing efficiency, and institutional coordination as prerequisites for investment attraction and technology deployment. While international literature emphasizes licensing modernization and harmonization, Brazilian experts additionally highlighted constitutional, institutional, and governance limitations specific to the national nuclear sector.

The Critical Incident Technique contributed to identifying concrete situations perceived by experts as illustrative of these institutional barriers. Rather than focusing exclusively on personal operational incidents, the adapted CIT approach enabled specialists to discuss regulatory discontinuities, delays in strategic projects, lack of long-term planning, and uncertainties surrounding private participation in nuclear activities. These elements emerged repeatedly in the interviews and were subsequently categorized within the regulatory and institutional analytical dimension.

International experiences mentioned by interviewees — particularly those from Canada, the United Kingdom, and the United States — suggest that regulatory adaptation can significantly reduce uncertainty and accelerate deployment while maintaining safety standards. Experts emphasized that Brazil could benefit from international cooperation and harmonization initiatives instead of developing entirely isolated licensing approaches.

5.2. Economic Viability and Financing Challenges

Economic viability concerns identified by 44.4% of interviewees reflect broader international discussions regarding first-of-a-kind SMR projects. Both the literature review and the interviews indicated that initial deployment costs, financing risks, and market uncertainties remain major obstacles for commercialization. However, experts also emphasized that SMRs present opportunities unavailable to large conventional reactors, especially in distributed industrial applications requiring reliable low-carbon energy. The interviews revealed that sectors such as petrochemicals, mining, offshore operations, and hydrogen production may provide economically viable entry points for SMR deployment in Brazil.

The articulation between bibliometric analysis and interviews demonstrated consistency regarding the importance of innovative financing models, including: public-private partnerships; development bank participation; long-term power purchase agreements; industrial self-generation arrangements.

The adapted CIT methodology proved useful in identifying institutional and financial conditions perceived as critical for investment attractiveness. Several experts referred to previous Brazilian infrastructure projects and nuclear-sector discontinuities as examples of how governance instability and policy uncertainty negatively affect long-term financing capacity.

5.3. Capacity Building and Technological Infrastructure

The interviews reinforced that successful SMR deployment depends not only on technological availability but also on workforce qualification, institutional capacity, and industrial infrastructure development. Although Brazil possesses accumulated expertise derived from Angra reactors, fuel cycle activities, research institutes, and naval nuclear programs, experts emphasized that SMRs require additional competencies in: modular construction; digital instrumentation and control; cybersecurity; advanced materials; integrated safety systems.

The bibliometric review similarly identified human resource development and supply chain qualification as recurrent themes in international SMR discussions. The triangulation between literature findings and interviews strengthened the interpretation that technological innovation alone is insufficient without parallel institutional and educational investments.

The expert interviews also highlighted concerns regarding workforce aging and the limited number of specialized educational programs capable of supporting future advanced reactor deployment. In this context, experts emphasized the importance of universities, research institutes, and international cooperation initiatives for knowledge transfer and professional training.

5.4. Public Acceptance, Communication, and Social Legitimacy

Public acceptance emerged as a relevant social dimension associated with SMR implementation, although it appeared less frequently than regulatory and economic barriers. The interviews revealed that experts perceive transparent communication and institutional credibility as essential conditions for building long-term social legitimacy for nuclear technologies.

The bibliometric analysis similarly demonstrated that social perception, risk communication, and stakeholder engagement constitute recurring concerns in the international literature on advanced nuclear technologies. Experts noted that historical nuclear accidents continue to influence public perception despite substantial technological advances in passive safety systems and reactor design.

The adapted Critical Incident Technique enabled participants to discuss not only specific communication failures observed historically in the nuclear sector but also broader institutional experiences related to public trust, political resistance, and societal risk perception. This broader interpretation of "critical incidents" proved particularly useful in a context involving emerging technologies and public policy debates rather than exclusively operational events.

The interviews suggested that communication strategies should: explain safety concepts in accessible language; address risks transparently; demonstrate environmental and socioeconomic benefits; involve communities early in decision-making processes; strengthen institutional trust.

5.5. Political Commitment and Institutional Stability

One of the most recurrent themes throughout the interviews was the need for continuous state nuclear policy independent of short-term political cycles. Experts argued that long-term institutional stability is indispensable for technologies such as SMRs, whose deployment horizons extend across decades.

The interviews demonstrated that experts perceive policy discontinuity as a major historical limitation affecting the Brazilian nuclear sector. The bibliometric findings reinforced this interpretation by highlighting the importance of stable governance frameworks for advanced reactor commercialization internationally.

The adapted CIT approach enabled interviewees to refer to institutional discontinuities, delays in strategic programs, and interruptions in public investments as critical examples illustrating governance fragility in Brazil. These observations were classified within the institutional and regulatory analytical dimension due to their direct influence on investment confidence and strategic planning capacity.

Institutional theory, discussed in the theoretical framework, helps explain why predictable rules, long-term planning, and governance continuity are fundamental conditions for technological adoption and infrastructure investment. The findings suggest that SMR implementation in Brazil depends not only on technical feasibility but also on the creation of stable institutional arrangements capable of sustaining long-term energy policies.

5.6. Integration of SMRs into Brazil's Energy Transition

The interviews and bibliometric analysis converged in recognizing SMRs as a potential complementary technology within Brazil's predominantly renewable energy matrix. Experts

emphasized that SMRs may contribute to: grid reliability; industrial decarbonization; hydrogen production; energy supply for remote regions; diversification of low-carbon energy sources.

The results suggest that SMRs should not be interpreted as substitutes for renewable sources, but rather as complementary technologies capable of enhancing energy security and supporting hard-to-abate industrial sectors.

Several interviewees highlighted the relevance of non-electric applications, particularly industrial heat generation, offshore operations, mining activities, and cogeneration systems. These findings are consistent with recent international discussions identified in the literature review concerning the broader role of advanced reactors in integrated decarbonization strategies.

Overall, the triangulation between bibliometric evidence and expert assessments strengthened the analytical consistency of the study and demonstrated that the critical success factors associated with SMR implementation in Brazil involve interconnected regulatory, institutional, economic, technological, and social dimensions.

6. CONCLUSIONS

This study demonstrated that SMRs represent a promising complementary technology for Brazil's energy transition and industrial decarbonization. The integration between bibliometric analysis and expert interviews enabled the identification of critical success factors involving regulatory, institutional, economic, technical, and social dimensions.

The results indicate that regulatory inadequacy, capacity-building needs, risk management challenges, and economic viability concerns constitute the principal barriers identified by experts to SMR deployment in Brazil. Conversely, opportunities associated with industrial applications, distributed generation, hydrogen production, and public-private partnerships suggest significant potential for supporting national decarbonization and energy security goals.

The triangulation between international literature and expert perceptions strengthened the robustness of the findings and allowed identification of challenges specific to the Brazilian context. Furthermore, the adaptation of the Critical Incident Technique proved appropriate for investigating emerging technologies and governance-related issues associated with SMR implementation.

Overall, the study reinforces that successful SMR deployment in Brazil depends not only on technological maturity but also on stable governance, regulatory modernization, workforce qualification, and transparent communication strategies.

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Writing: Review & Editing: ALRO, MLM
Visualization: ALRO, MLM

CONFLICT OF INTEREST

The author declares no conflicts of interest related to this research.

DATA AVAILABILITY STATEMENT

Interview transcripts and qualitative data are not publicly available due to confidentiality commitments made to research participants. Aggregated data supporting the findings are available from the corresponding author upon reasonable request and subject to participant privacy protections.

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