

Institutional Factors Enabling Research-to-Operations Conversion in a Military Health ICT: The Case of the Institute of Aerospace Medicine within SINAER

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Abstract

Purpose: This study investigates the institutional factors that enabled the Institute of Aerospace Medicine (IMAE), a military health organization within the Brazilian Aeronautics Innovation System (SINAER), to convert academic research into operational products and assesses evidence of institutional maturity underlying this capacity.

Methods: A qualitative exploratory case study was conducted, based on systematic document analysis and normative triangulation with SINAER regulations (2022–2026). Two success cases were examined: the Anti-G Straining Maneuver (AGSM) with muscular biofeedback and the hypoxia research line.

Results: IMAE delivered 13 products in four years (5 articles, 4 theses, 3 presentations, 2 technological products, 1 funding capture). The AGSM with biofeedback crossed the "valley of death," reaching Technology Readiness Level (TRL) 8–9 and was implemented in the Brazilian Air Force Physiological Adaptation Course. Normobaric hypoxia protocols advanced to TRL 5–6 with prospects for technology transfer to civil aviation.

Conclusions: IMAE consolidated itself as a mature Science and Technology Institution within SINAER, demonstrating that military health organizations can convert scientific expertise into operational products that strengthen national sovereignty and flight safety. The SINAER governance model, with DCTA as a centralized Technology Transfer Office, provided the institutional conditions enabling this transition, offering lessons learned for other military health ICTs.

JEL Classification: O31, O32, O33, O38, H56

Introduction

In the defense sector, Science, Technology and Innovation (ST&I) constitute strategic pillars in consolidating national sovereignty and operational capacity. Supported by the Brazilian Innovation Law (Law No. 10,973/2004) and its associated regulatory framework — including Law No. 13,243/2016 and Decree No. 9,283/2018 — military institutions have sought to reduce dependence on foreign sources of sensitive Technologies and strengthen the Defense Industrial Base (DIB) (Chesbrough, 2003; Cohen & Levinthal, 1990; Mowery, 2010). Within this context, public Science and Technology Institutions (ICTs) have become central agents in the national innovation system, responsible for generating knowledge and technology that contribute to economic and social development (Brasil, 2004).

However, the transition of military health organizations from operational service delivery to formally structured ICTs remains an underexplored phenomenon in the innovation literature. While significant attention has been devoted to technology transfer processes in civilian universities and research institutes (Santos & Toledo, 2012; Torkomian, 2009; Fernandes et al., 2018), and, more recently, to systemic innovation governance models within the Brazilian Air Force (Neves et al., 2026), the specific *institutional mechanisms* through which military health organizations convert scientific expertise into

operational products that enhance flight safety and combat effectiveness - have not been systematically examined.

This article addresses the following research question: What institutional factors enabled the Institute of Aerospace Medicine (IMAE) – a military health organization operating within the Brazilian Aeronautics Innovation System (SINAER) – to convert academic research into operational products, and what evidence indicates that this conversion capacity reflects institutional maturity as a science and technology institution? To investigate this question, a qualitative exploratory case study was conducted based on systematic document analysis of institutional reports (2022–2026) and normative triangulation against SINAER regulations, following the methodological approaches of Yin (2018) and Bowen (2009).

The Institute of Aerospace Medicine (IMAE), traditionally recognized for its role in aeronautical health assessment and pilot selection, faced the challenge of establishing itself as a formal ICT within SINAER, overcoming the dichotomy between operational healthcare service delivery and applied research. The Aeronautics Innovation System (SINAER), established by Ordinance No. 881/GC3 of 2017, coordinates ST&I activities within the Aeronautics Command (COMAER), with the Department of Aerospace Science and Technology (DCTA) as its centralized Technology Transfer Office (NIT) (Força Aérea Brasileira, 2017). As Neves et al. (2026) demonstrate, the DCTA – through its Innovation Management Coordination (CGI/DCTA) – performs functions that transcend those of civilian academic NITs, acting as a boundary organization that simultaneously balances sovereignty requirements, military compliance, and market agility. This institutional architecture, which supports 17 ICT within SINAER, provided the enabling conditions for IMAE's consolidation as an ICT.

The theoretical relevance of this study lies in its integration of three analytical frameworks that have rarely been combined in the Brazilian defense innovation literature. First, the absorptive capacity framework (Cohen & Levinthal, 1990) – which explains how organizations recognize the value of new information, assimilate it, and apply it productively – provides a lens for understanding IMAE's ability to translate operational demands (e.g., G-LOC prevention, hypoxia training) into structured research programs. Second, the concept of the valley of death in innovation (Markham, 2002; Auerswald & Branscomb, 2003) – the critical gap between laboratory research and operational application – serves as the central metaphor for evaluating IMAE's capacity to move technologies from basic research (TRL 2–3) to full operational implementation (TRL 8–9). Third, the entrepreneurial state perspective (Mazzucato, 2013) frames the role of the state, through its military ICTs, in directly providing critical services in which the private sector has insufficient investment incentives. These frameworks are complemented by the literature on open innovation (Chesbrough, 2003) and defense innovation systems (Mowery, 2010; Ruttan, 2006), which situates the IMAE case within the broader dynamics of military R&D and technology transfer.

The practical relevance of this study is threefold. First, it presents concrete examples of successful innovation - the Anti-G Straining Maneuver (AGSM) with muscular biofeedback and the hypoxia research

line (hypobaric and normobaric) — that illustrate how the SINAER normative framework enables the delivery of technological solutions for high-criticality applications. The AGSM with biofeedback, having reached TRL 8–9 and been implemented in the Physiological Adaptation Course (EAF) of the Brazilian Air Force, demonstrates the complete innovation cycle from bench research to an operational product. Second, the analysis contributes to the emerging literature on military health ICTs - a field still emerging in Brazilian scholarship, particularly when compared to the more established literature on technology transfer processes in defense (Neves et al., 2026; Leite et al., 2023) and civilian university-industry interactions (Etzkowitz, 2003; Garnica & Torkomian, 2009). Third, the IMAE experience offers transferable lessons for other military health organizations within the Brazilian Armed Forces — including the Army and Navy — that operate under similar institutional arrangements in which multiple STIs share a single centralized NIT.

This article is structured as follows. The next section presents the theoretical framework, covering defense innovation systems, the SINAER architecture, and innovation in military health. The methodology section describes the qualitative case study approach, data sources, and analytical procedures. The results section examines IMAE's institutional profile and the two success cases in detail. The discussion section analyzes the findings through the theoretical lenses outlined above, addressing the innovation cycle, the enabling role of SINAER, sustainability challenges, and lessons for other military health ICTs. Finally, the conclusion synthesizes the contributions, acknowledges limitations, and proposes a future research agenda.

Analytical Lenses for Military Health ICTs

The theoretical foundation of this study draws on three interconnected streams of literature: defense innovation systems and public ICTs, the "valley of death" in technology maturation, and innovation governance within military health organizations. Together, these streams provide the analytical lenses through which the institutional trajectory of the Institute of Aerospace Medicine (IMAE) is examined.

Defense Innovation Systems and Public ICTs

Public Science and Technology Institutions (ICTs) are organizations whose institutional mission encompasses research, technological development, and innovation and that are funded wholly or partially by public resources. In Brazil, these include federal universities, research institutes, and military organizations with R&D capacity. The Innovation Law (Law No. 10,973/2004) and its subsequent regulatory framework — including Law No. 13,243/2016 and Decree No. 9,283/2018 — recognized ICTs as strategic actors in public policy responsible for generating knowledge and technology that contribute to the Brazil's economic and social development (Brasil, 2004; Brasil, 2016; Brasil, 2018).

Technology Transfer Offices (NITs) are administrative structures responsible for managing innovation policy, intellectual property protection, and technology transfer within ICTs. According to Article 16 of the Innovation Law, every NIT must perform functions such as assessing the patentability of research

results, advising researchers on IP protection, negotiating partnership and licensing agreements, and managing royalties (Santos & Toledo, 2012; Torkomian, 2009). The NIT acts as an intermediary between the internal scientific community and industry - a function that Torkomian (2009) identified as critical for partnership success. However, as Fernandes et al. (2018) observed, even institutions with extensive experience in technology transfer management still face substantial barriers in mediating university-company relationships and facilitating the transfer of academic knowledge to the business sector.

University-industry-government interaction that underpins this process is conceptualized through Triple Helix model (Etzkowitz, 2003; Etzkowitz & Zhou, 2017), in which the government acts beyond its traditional regulatory role to actively foster innovation, while universities generate new knowledge to be brought to market by companies. In the Brazilian defense context, this model has historical roots: the creation of the Aeronautics Institute of Technology (ITA) and its engineering programs – which ultimately led to the establishment of Embraer – represents a paradigmatic case of Triple Helix dynamics preceding the formal articulation of the model itself (Suzigan & Albuquerque, 2008; Matos, 2022). The SINAER framework, as Neves et al. (2026) demonstrate, extends this logic by embedding a systemic innovation governance model within the military structure, in which the Department of Aerospace Science and Technology (DCTA) functions as a centralized NIT for 17 ICTs.

Complementing the Triple Helix perspective, the concept of absorptive capacity (Cohen & Levinthal, 1990) provides a framework for understanding how organizations recognize the value of new information from external sources, assimilate it, and apply it productively. In the context of military ICTs, absorptive capacity is not merely a function of R&D investment – it depends on the organization's ability to translate operational demands (e.g., physiological risks in high-performance flight) into structured research questions, and subsequently into technological solutions. This translation process is what distinguishes a mature ICT from an isolated research group.

The "Valley of Death" and Technology Readiness Levels in Defense Innovation

A central challenge for any ICT seeking to convert research into operational products is the so-called "valley of death" – the critical gap between laboratory research and market deployment or operational application, in which promising technologies often fail due to insufficient funding, inadequate institutional support, or a lack of bridging mechanisms (Markham, 2002; Auerswald & Branscomb, 2003). In the defense sector, this valley is particularly deep due to the highly critical nature of military applications, prolonged development cycles and regulatory requirements that govern defense procurement (Mowery, 2010; Ruttan, 2006).

The Technology Readiness Level (TRL) scale, originally developed by NASA and subsequently adopted by defense organizations worldwide, provides a common metric for tracking technology maturation from basic principles (TRL 1) to full operational deployment (TRL 9). In the Brazilian defense context, the TRL framework has been integrated into SINAER's innovation management guidelines (NSCA 80 – 1/2024),

enabling military ICTs to systematically monitor the progression of their projects and identify precisely where their projects encounter the valley of death. For military health ICTs such as IMAE, crossing this valley means not only developing a functional prototype but also integrating it into operational training curricula – a process that requires institutional mechanisms that bridge the gap between academic validation and operational certification.

The SINAER's Normative and Organizational Architecture

The Aeronautics Innovation System (SINAER), established by Ordinance No. 881/GC3 of 2017, coordinates ST&I activities within the Aeronautics Command (COMAER), with the DCTA serving as its centralized NIT (Força Aérea Brasileira, 2017). As Neves et al. (2026) document, the Innovation Management Coordination (CGI/DCTA) performs functions that transcend those of civilian academic NITs, acting as a boundary organization that simultaneously balances sovereignty requirements, military compliance, and market agility – a role analogous to international agencies such as DARPA (USA) and the Defence and Security Accelerator (UK) (Mowery, 2010; Hartley, 2014). The systemic governance model adopted by SINAER was a direct response to communication and coordination problems among the various research and development institutions involved, enabling more effective management of innovation-related processes (Leite et al., 2023).

The normative framework is organized through Air Force Command System Standards (NSCAs). NSCA 80 – 1/2024 establishes guidelines for Technological Innovation Management, while NSCA 80 – 2/2019 regulates Intellectual Property and Technology Transfer (Força Aérea Brasileira, 2024a; 2019). NSCA 80 – 10/2024 introduces the category of Privileged Technological Information (ITP), which allows sensitive R&D knowledge to be afforded "restricted access" protection, ensuring traceability and intellectual property security without requiring the full rigor of state security classification, thereby facilitating collaboration with civilian entities (Força Aérea Brasileira, 2024b). ICA 80 – 16 details the administrative flow for ST&I partnerships in four phases: (1) prospecting and expression of interest; (2) institutional alignment and scope definition; (3) procedural instruction with elaboration of the Innovation and Partnership Project (PIP); and (4) agreement execution and publication.

This architecture has a distinctive feature compared to civilian innovation systems: its legal advisory structure. While most civilian STIs in Brazil are advised by the Federal Attorney General's Office (PGF) through the Permanent Chamber of Science, Technology & Innovation (CP-CT&I/PGF), organizations within the direct federal administration – including FAB's STIs – are advised by the Office of the Comptroller General (CGU) through federal attorneys. As Neves et al. (2026) explain, the CGU's interpretation requires that licensing and technology transfer agreements be linked to an ST&I project, in accordance with Normative Guideline No. 7/2021 issued by the Specialized Virtual Residual Federal Legal Advisory Office. This legal requirement shapes how innovation projects are structured and documented within SINAER.

Innovation in Military Health and Dual-Use Technologies

Innovation in military health differs from civilian health innovation in three fundamental respects. First, the ultimate objective is to enhance the operational capability of the armed forces — health solutions must enhance, not merely restore, human performance in extreme environments such as high-G maneuvering and hypobaric conditions. Second, the dual-use potential is explicit: technologies developed for pilot physiological training — such as normobaric hypoxia protocols and the AGSM with biofeedback - can be applied in civil aviation and public health, generating social value beyond the military sphere (Cowan & Foray, 1995; Mowery, 2010). Third, the institutional environment imposes security constraints and chain-of-command structures that can both hinder and enable innovation: hierarchy accelerates implementation once decisions are made at the strategic level but can slow bottom-up initiatives.

The concept of dual-use innovation - referring to technologies with both military and civilian applications — has been extensively discussed in the defense innovation literature. Cowan and Foray (1995) highlight the economic dilemmas associated with dual-use technologies, particularly the tension between the spillover benefits of military R&D and the restrictions imposed by security requirements. Mowery (2010) and Ruttan (2006) further demonstrate that military procurement has historically driven technological development in areas ranging from semiconductors to aerospace, with substantial spillover effects on civilian economies. In the Brazilian context, the IMAE's laboratory infrastructure - including a human centrifuge and hypobaric and normobaric chambers - exemplifies this dual-use potential: the capacity to develop training protocols for commercial and executive aviation demonstrates that military health ICTs have social relevance that extends beyond their primary mission.

Beyond the strict classification of the Oslo Manual, the IMAE case can be understood through the lens of public sector innovation literature, which defines innovation as the implementation of new or significantly improved services, processes, or organizational methods that generate public value (Bloch & Bugge, 2013). From this perspective, the AGSM with biofeedback constitutes an innovation not because it generated a patentable product, but because it created a new organizational model for aerospace physiological training — a model that produced measurable public value by reducing G-LOC risk, eliminating dependence on foreign sources, and expanding access to cutting-edge training at a fraction of the cost of international training.

This aligns with Mazzucato's (2013) concept of the entrepreneurial state, in which the state - through its military ICTs - directly undertakes the provision of critical services in which the private sector lacks sufficient incentives to invest. The Directorate of Health's decision to establish IMAE as an ICT reflects this logic: the state recognized that the development of aerospace physiological training solutions, given the limited size of the commercial market and its high strategic importance to national sovereignty, required direct public investment and institutional innovation.

Synthesis of Analytical Frameworks

The three streams outlined above are integrated into the present analysis as follows. The defense innovation systems literature provides the macro-institutional context for understanding SINAER and the role of ICTs within it. The valley of death concept and TRL framework offer a meso-level analytical tool for evaluating the progression of IMAE's two successful cases from basic research to operational implementation. The literature on military health innovation and dual-use technologies supplies the micro-level lens for interpreting the distinctive features of aerospace medicine as a field of technological development. Together, these frameworks allow the study to move beyond a purely descriptive account of IMAE's outputs toward an analytical assessment of its institutional maturity as a strategic ICT within the Brazilian defense innovation ecosystem.

Methodology

Research Design

A qualitative exploratory case study design was adopted, following the single-case method with embedded units of analysis (Yin, 2018). The case study approach is appropriate when the research question addresses a contemporary phenomenon within its real-life context, particularly when the boundaries between the phenomenon and the context are not clearly evident – as is the case with the institutional transition of a military health organization into a formal Science and Technology Institution (Yin, 2018; Stake, 1995). The single-case design was chosen because IMAE represents a revelatory case: an organization that, over approximately four years, established an innovation management structure and produced measurable technological outputs within a defense innovation system - a phenomenon that remains sparsely documented in Brazilian innovation literature (Neves et al., 2026; Leite et al., 2023).

The unit of analysis is the Institute of Aerospace Medicine (IMAE) as an organization, with two embedded subunits based on: (i) the Anti-G Straining Maneuver (AGSM) with muscular biofeedback project, and (ii) the hypoxia research line (hypobaric and normobaric protocols). These subunits were selected according to two criteria: (a) they represent the complete innovation cycle, from basic research (TRL 2–3) to operational implementation (TRL 8–9) or advanced development (TRL 5–6), and (b) they are the only projects within IMAE's portfolio for which systematic documentation spanning the entire 2022–2026 period were available at the time of data collection. This embedded design allows the study to examine how the same institutional context (IMAE-SINAER) produced different technological maturation trajectories across distinct research lines.

The 2022–2026 period was defined based on two institutional milestones. The starting point (2022) corresponds to the formal establishment of IMAE's Research and Innovation Subdivision (SDPI) as the coordinating unit for ST&I activities, thereby establishing systematic record-keeping for scientific and technological production. The endpoint (2026) corresponds to the latest complete institutional report available at the time of data collection (IMAE, 2026). This four-year window captures both the initial consolidation phase and the first cycle of tangible outputs, from academic publications to operational products implemented in Air Force training curricula.

Data Sources and Documentary Corpus

Data were collected through systematic document analysis, following the procedures recommended by Bowen (2009) for use in organizational studies. The document corpus comprised four categories of sources:

1. Institutional records of scientific and technological production: the "IMAE ST&I Success Case Reports" (June 2026), which provide a consolidated inventory of all products delivered by the SDPI in the 2022–2026 period, including journal articles, master's theses, conference presentations, technological products, and external funding secured. These reports also contain the project-level documentation for the AGSM and hypoxia cases, including descriptions of technology maturation, implementation milestones, and current status.
2. Normative and regulatory documents: (a) Ordinance No. 881/GC3 of 2017, which established SINAER; (b) NSCA 80 – 1/2024 (Technological Innovation Management); (c) NSCA 80 – 2/2019 (Intellectual Property and Technology Transfer); (d) NSCA 80 – 10/2024 (Privileged Technological Information); and (e) ICA 80 – 16 (administrative procedures for ST&I partnerships). These documents were analyzed to characterize the institutional framework within which IMAE operates and to assess the extent to which its innovation management practices comply with the applicable regulatory framework.
3. Legal framework instruments: Law No. 10,973/2004 (Innovation Law), Law No. 13,243/2016 (Legal Framework for Innovation), and Decree No. 9,283/2018 (regulatory decree). These were analyzed to contextualize the legal conditions that enabled the implementation of the ICT model.
4. Scientific literature: peer-reviewed articles and academic books on defense innovation systems (Mowery, 2010; Ruttan, 2006), public ICT management (Santos & Toledo, 2012; Torkomian, 2009), technology transfer in the Brazilian Air Force (Neves et al., 2026; Leite et al., 2023), innovation governance (Chesbrough, 2003; Etzkowitz, 2003), and absorptive capacity (Cohen & Levinthal, 1990). These secondary sources informed the theoretical framework and provided comparative benchmarks for the analysis.

A total of 37 documents were analyzed across the four categories. Table 1 (in the Results section) summarizes the quantitative indicators extracted from the institutional records.

Analytical Procedures

Data analysis followed a structured triangulation protocol, based on Flick's (2018) framework for qualitative triangulation. The analysis proceeded in three stages:

Stage 1 – Normative mapping. The regulatory documents (category ii) and legal framework documents (category iii) were analyzed to develop a reference model of the institutional requirements for full compliance by an ICT within SINAER. This model served as the institutional benchmark against which IMAE's practices were compared. Key variables extracted from this mapping included existence and

operation of an innovation cell, formalization of technology transfer processes, compliance with intellectual property guidelines, and integration with the centralized NIT (CGI/DCTA).

Stage 2 – Output analysis. The institutional records (category i) were analyzed quantitatively and qualitatively. Quantitatively, the 15 technology and knowledge products were classified by type and delivery status and, for the two case studies, by associated TRL (Mankins, 1995). Qualitatively, the project documentation for the AGSM and hypoxia case studies was examined to reconstruct the innovation trajectory of each case, from the initial research question to the current stage of operational implementation or technology transfer.

Stage 3 – Cross-stage analysis. The findings from Stages 1 and 2 were cross-referenced to assess institutional maturity. Three analytical questions guided this stage: (a) does IMAE's documented innovation flow (Stage 2) align with SINAER's normative requirements (Stage 1)? (b) at what points on the TRL scale did each case encounter the "valley of death" (Markham, 2002; Auerswald & Branscomb, 2003), and what mechanisms enabled each case to cross it? and (c) what evidence indicates that the institutional capacity developed can be sustained beyond the initial four-year period?

This triangulation design mitigates the inherent limitations of relying on a single data source and enables an assessment of whether the SDPI/IMAE's performance fulfills the complete innovation cycle as defined in both SINAER norms and the technology management literature (Bowen, 2009; Flick, 2018).

Methodological Limitations

Three methodological limitations are acknowledged. First, reliance on self-reported institutional data - the IMAE Success Case Reports - introduces potential desirability bias in the reporting of outputs. This limitation was mitigated by cross-checking with independent sources (published articles, registered theses, and official publication records) wherever possible. Second, the single-case design restricts external validity; the findings are analytically generalizable to the theoretical propositions of defense innovation systems (Yin, 2018) rather than statistically generalizable to a population of military ICTs. Third, the absence of direct economic impact metrics (e.g., cost savings from accident reduction, return on investment in R&D infrastructure) limits the analysis to output indicators rather than outcome indicators. This limitation is addressed in the proposed future research agenda.

Results

This section presents the findings of the document analysis organized around the two embedded units of the case study: the Anti-G Straining Maneuver (AGSM) with muscular biofeedback and the hypoxia research line (hypobaric and normobaric protocols). The results are reported in three subsections: first, an overview of IMAE's institutional profile and aggregate output indicators; second, the detailed trajectory of each case on the TRL scale; and third, a cross-case synthesis of the patterns observed.

Institutional Profile and Aggregate Output

The Institute of Aerospace Medicine, through its Research and Innovation Subdivision (SDPI), has structured its innovation activities around a translational research model that converts operational demands from the Physiological Adaptation Course (EAF) and other FAB training programs into research questions, and subsequently into technological products. The SDPI was formally established in 2022 with the mandate to coordinate ST&I projects, manage intellectual property, and interface with the centralized Technology Transfer Office (CGI/DCTA). As of June 2026, the SDPI had developed a portfolio of 15 technological and knowledge products across six categories, as summarized in Table 1.

Table 1
IMAE Scientific and Technological Outputs (2022–2026)

Product Category	Delivered	In Progress	Total
Journal Articles	5	0	5
Master's Theses	3	1	4
Conference Presentations	3	0	3
Technological Products	1	1	2
External Funding Secured	1	0	1
Total	13	2	15

Source: Adapted from IMAE ST&I Success Case Reports (2026).

Table 1 shows 15 outputs across five categories: 5 journal articles, 3 completed master's theses and 1 in progress, 3 conference presentations, 1 delivered technological product and 1 in progress, and 1 external funding award. Of these, 13 were delivered and 2 were in progress as of June 2026.

Case 1 – Anti-G Straining Maneuver (AGSM) with Muscular Biofeedback

The AGSM with biofeedback project originated from a well-defined operational problem: G-induced Loss of Consciousness (G-LOC) remains one of the primary physiological risk factors for accidents involving high-performance aircraft. This line of research began with the analysis of electromyographic (EMG) signals to identify the most efficient muscle activation patterns during the respiratory and straining maneuver performed by fighter pilots under + Gz acceleration.

The innovation trajectory of this project, traced over four years and seven completed outputs, is summarized in Table 2.

Table 2

Innovation Trajectory: AGSM with Table 2 – Innovation Trajectory of the AGSM Biofeedback Project

Output Type	Specific Output	Year	Estimated TRL
Conference Presentation	Qualitative EMG Analysis in AGSM Sessions	2022	TRL 2–3
Conference Presentation	EMG Signal Analysis in AGSM Sessions	2023	TRL 3
Master's Thesis	Pires Junior, P. (2024) – EMG Signal Analysis for AGSM Optimization	2024	TRL 4
Article in a National Journal	Revista Agulhas Negras (2024)	2024	TRL 4
International Article	Aerospace Medicine and Human Performance (2025)	2025	TRL 5–6
Technological Product	AGSM real-time biofeedback system	2025	TRL 7–8
Operational Implementation	AGSM with biofeedback integrated into EAF training	2025–2026	TRL 8–9
Master's Thesis (in progress)	Campello Júnior, L. C. S. (2026) CEO-Ca Protocol	2026	In Progress

Source: Adapted from IMAE Reports (2026). TRL classification follows Mankins (1995).

The AGSM project progressed from TRL 2–3 (2022) to TRL 8–9 (2025–2026), spanning seven deliverables over approximately four years. Academic outputs included two conference presentations (2022, 2023), one master's thesis (2024), and two journal articles (2024, 2025). The technological product - a real-time biofeedback system for AGSM - reached TRL 7–8 in 2025 and was subsequently integrated into the curriculum of the Physiological Adaptation Course (EAF), thereby reaching TRL 8–9. A second master's thesis on the CEO-Ca Protocol is in progress (2026).

Case 2 – Hypoxia in Controlled Environments (Hypobaric and Normobaric)

The IMAE hypoxia research line is structured around two complementary approaches: hypobaric hypoxia (reduced atmospheric pressure in the hypobaric chamber) and normobaric hypoxia (reduced oxygen concentration at ambient pressure). Together, these approaches address the operational need to train aircrew to recognize and respond to hypoxic states - a critical skill for flight safety at altitude.

The production trajectory is summarized in Table 3.

Table 3
Innovation Trajectory: Hypoxia Research Line

Subfield	Output Type	Specific Output	Year	Estimated TRL
Hypobaric	Systematic Review Article	Studies in Health Sciences 6 (2025)	2025	TRL 1–2
Hypobaric	Article in a National Journal	Revista da UNIFA 38 (2025)	2025	TRL 2–3
Hypobaric	Master's Thesis	Completed thesis	2024	TRL 3–4
Normobaric	External Funding Secured	Royalties Call – Infrastructure Modernization	2025	–
Normobaric	National Article	RGSA/ANPAD (2025) – Scoping Protocols	2025	TRL 3–4
Normobaric	Conference Presentation	Operational Performance of Aircrew	2025	TRL 4
Normobaric	Technological Prototype (in progress)	Customized protocol for commercial aviation	2026	TRL 5–6

Source: Adapted from IMAE Reports (2026).

The hypoxia research line comprises two subfields with distinct maturity levels. The hypobaric subfield produced one systematic review article (TRL 1–2), one article in a national journal (TRL 2–3), and one completed master's thesis (TRL 3–4). The normobaric subfield produced one external funding award (Royalties Call, 2025), one national article (TRL 3–4), one conference presentation (TRL 4), and one technological prototype under development at TRL 5–6 (customized protocol for commercial aviation, 2026). No normobaric output has yet reached TRL 7 or higher.

Cross-Case Synthesis

When examined together, the two cases present distinct technological maturation trajectories within the same institutional context. Table 4 summarizes the comparative progression.

Table 4
Cross-Case Comparison of Technological Maturation

Dimension	AGSM with Biofeedback	Hypoxia Research Program
Starting TRL	TRL 2–3 (2022)	TRL 1–2 (2024–2025)
Highest TRL Reached	TRL 8–9 (2025–2026)	TRL 5–6 (2026)
Time span	4 years	2–3 years
Total Outputs	7 delivered + 1 in progress	6 delivered + 1 in progress
Funding mechanism	Internal operational demand (EAF)	External call (Royalties Call)
Primary application	Military training (FAB)	Civil aviation (dual-use)

Source: Adapted from IMAE Reports (2026).

The AGSM case progressed from TRL 2–3 to TRL 8–9 over four years, driven by internal operational demand from the EAF. The hypoxia case progressed from TRL 1–2 to TRL 5–6 over two to three years, primarily funded through an external Royalties Call. Both cases operated under the same SINAER normative framework and the SDPI coordination structure. The AGSM case completed the full cycle from basic research to operational implementation; the hypoxia case reached advanced prototyping stage with technology transfer to civil aviation as the next step.

Discussion

Innovation Cycle and Technological Maturity

The AGSM with biofeedback case provides the clearest evidence that the IMAE crossed the "valley of death" — the critical gap between laboratory research and operational application, in which promising technologies often fail due to insufficient funding, inadequate institutional support, or lack of bridging mechanisms (Markham, 2002; Auerswald & Branscomb, 2003). The project evolved from basic electromyographic research (TRL 2–3) to a technological product implemented in the Physiological Adaptation Course of the Brazilian Air Force (TRL 8–9) within approximately four years. This progression merits analytical attention not merely because it succeeded, but because of the specific mechanisms that enabled it.

The project crossed the valley of death between TRL 4–5 (academic validation of EMG signal patterns) and TRL 7–8 (functional prototype in the centrifuge). The bridging mechanism was the integration of the SDPI's project management with the CGI/DCTA's legal and administrative support, which enabled the transition from a research protocol to a biofeedback system integrated into the centrifuge training environment within approximately 18 months — a relatively short cycle in defense innovation, in which prolonged development timelines are the norm (Mowery, 2010; Ruttan, 2006). The contrast between the two cases is informative in this regard. The AGSM case crossed the valley of death through operational

pull: the direct demand from the EAF for a G-LOC mitigation solution created a clear application pathway, reducing the uncertainty that typically characterizes the TRL 4–7 transition (Mankins, 1995). The hypoxia case, by contrast, has yet to cross the valley at the TRL 5–6 stage, and its crossing depends on external funding push - specifically, funding from the Royalties Call for infrastructure modernization and partnerships with civil aviation companies. This asymmetry suggests that the IMAE, while institutionally mature, is not immune to the structural challenge that Auerswald and Branscomb (2003) identified as the "Darwinian sea" of early-stage technology financing: technologies that lack an immediate operational customer face higher barriers to maturation, regardless of the institutional context.

When analyzed together, the two cases reveal complementary patterns of institutional maturity within IMAE. The AGSM case demonstrates the complete innovation cycle under the SINAER framework, from basic physiological research (TRL 2) to operational implementation in military training (TRL 9). The hypoxia case demonstrates an earlier-stage but strategically broader trajectory, targeting dual-use applications and relying on external resource mobilization. Both cases share three common enabling factors: (a) a structured project management approach by the SDPI, which maintained the research-to-product pipeline; (b) the regulatory support provided by the SINAER framework, including the CGI/DCTA's role as the centralized NIT, providing legal certainty for partnerships; and (c) the embeddedness of research within operational training demands, ensuring that the research questions addressed real operational needs rather than purely academic interests.

Translational Efficiency and Absorptive Capacity

The aggregate output data from Table 1, when interpreted through the lens of absorptive capacity (Cohen & Levinthal, 1990), reveal structural features of the IMAE's institutional model. The 5:4 ratio of journal articles to completed theses reflects a deliberate alignment between the academic training of military researchers and the Institute's research agenda — each master's thesis produced through the FAB's graduate programs at UNIFA and ITA was directly integrated into one of IMAE's research lines. This alignment suggests that the Institute systematically developed the human capital necessary to recognize, assimilate, and apply new knowledge to operational problems — a defining characteristic of absorptive capacity at the organizational level.

The 9:2 ratio of academic outputs (articles + theses) to technological products indicates a level of translational efficiency that exceeds what is typically observed in public ICTs. Fernandes et al. (2018) documented that most Brazilian ICTs face substantial barriers to converting academic knowledge into technological products. The IMAE's ratio, although based on a limited four-year window and a small number of products in absolute terms, suggests that the SDPI's structured project management — combined with the SINAER framework — may partially mitigate these barriers. However, this interpretation should be treated as suggestive rather than conclusive, given the small sample size and the absence of comparable longitudinal data from other military health ICTs.

The sequential structure of the AGSM project — in which each academic output (conference presentation, thesis, journal article) served as the foundation for the next technological step - further

illustrates this capacity. The EMG signal characterization published in 2023 provided the physiological parameters that defined the biofeedback algorithm. The validation study published in *Aerospace Medicine and Human Performance* (2025) served as the evidence base for the operational certification of the system. This sequential scaffolding — each publication providing the foundation for the next technological advance - is a replicable pattern among mature ICTs and reflects what Cohen and Levinthal (1990) describe as the dual role of R&D: generating new knowledge while simultaneously building the organization's ability to recognize and exploit externally generated knowledge.

SINAER as an Enabling Framework

The IMAE's consolidation did not occur in an institutional vacuum. It was enabled by the SINAER's regulatory and organizational framework, which coordinates ST&I activities within COMAER and allows military organizations to operate as public ICTs (Força Aérea Brasileira, 2017). The findings of this study complement those of Neves et al. (2026), who demonstrated that the CGI/DCTA — as SINAER's centralized NIT — provided the legal certainty necessary to structure innovation partnerships by balancing between sovereignty requirements, military compliance, and market agility. In IMAEs case, this intermediation function was reflected in the ability to translate SDPI research demands into administratively viable partnership projects, supported by the Innovation Law and its regulatory framework (Brasil, 2004; 2016; 2018).

The third significant feature of the AGSM case — implementation within the EAF at TRL 8–9 — demonstrates that the SINAER framework can support the full innovation cycle for a military health technology. The product was not merely tested in a laboratory environment but integrated into the operational training curriculum for FAB fighter pilots, directly enhancing flight safety and operational effectiveness in combat aviation. This outcome addresses the research question by showing that institutional conditions at IMAE — specifically the SINAER governance structure — were sufficient to enable the conversion of academic research into operational products that strengthen national sovereignty.

However, the cross-case analysis revealed a distinctive challenge within the SINAER framework. The legal advisory structure governing FAB's STIs — advised by the CGU through federal attorneys, rather than by the PGF as in civilian STIs — imposes specific documentary requirements, including the mandatory linkage of licensing and technology transfer agreements to an ST&I project (Normative Guideline No. 7/2021). As Neves et al. (2026) document, this requirement shaped the entire procedural architecture of the artifact developed to support technology transfer within SINAER. For the IMAE, this means that the transition from research to an operational product, while successful in the AGSM case, required navigating a complex regulatory environment that may not be tailored to the specific characteristics of military health innovation - in which the "client" is an internal operational unit (EAF) rather than an external company. The implication is that the very framework that enables innovation also imposes transaction costs that must be managed through specialized administrative capacity within the ICT.

This finding resonates with the broader literature on public ICTs in Brazil. Fernandes et al. (2018) documented that ICTs across Brazilian universities face persistent barriers in mediating researcher-industry relationships, despite the legal advances introduced by the Innovation Framework. Pires and Silva (2023) confirmed that most ICTs still struggle with the operationalization of technology transfer processes years after the enactment of Law No. 13,243/2016. In this context, the IMAE – supported by the SINAER systemic governance model – appears to have achieved a level of procedural integration that contrasts favorably with the challenges reported in civilian institutions. The question that remains open is whether this advantage is attributable to the military chain of command (which accelerates implementation once decisions are made) or to the specific design of the SINAER governance model (Leite et al., 2023).

Together, the 15 outputs documented in Table 1 – 13 completed and 2 in progress over approximately four years – represent an output level that, while modest in absolute terms, is significant for a military health organization that transitioned from operational service delivery to operating as a formal ICT over a relatively short period. The contrast with the challenges documented in the broader ICT literature (Fernandes et al., 2018; Pires & Silva, 2023) suggests that the SINAER's systemic governance model may offer institutional advantages that merit further investigation.

Dual-Use Potential and Public Value Creation

Beyond the strict measurement of TRL progression, the IMAE case illustrates a dimension of defense innovation that is often underestimated in the Brazilian literature: the dual-use potential of military health technologies. The normobaric hypoxia protocols, developed initially for FAB aircrew training, are currently being adapted for commercial and executive aviation. If successfully transferred, these protocols would represent a concrete case of military R&D generating public value beyond the defense mission – a phenomenon that Cowan and Foray (1995) identified as economically significant but institutionally fragile, since the incentives for military organizations to invest in civilian applications are structurally weaker than those for defense-specific applications.

The hypoxia research line also exemplifies a broader pattern documented in the defense innovation literature. Mowery (2010) and Ruttan (2006) demonstrated that military procurement has historically driven technological development in areas ranging from semiconductors to aerospace, with substantial spillover effects on civilian economies. In the Brazilian context, the IMAE's laboratory infrastructure - including a human centrifuge, hypobaric and normobaric chambers - represents a strategic asset whose value transcends its primary aeromedical mission. The capacity to develop training protocols for commercial aviation demonstrates that military health ICTs can function as what Mazzucato (2013) terms the entrepreneurial state: the state, through its military institutions, directly assumes the provision of critical services that the private sector has insufficient incentives to provide. However, the sustainability of this model depends on the development of institutional mechanisms that allow the ICT to capture and reinvest the returns generated by dual-use applications – a challenge that the IMAE has only partially addressed through the Royalties Call mechanism.

Sustainability and Institutional Challenges

Despite the documented achievements, three challenges merit attention regarding the long-term sustainability of IMAE as an ICT.

First, the dependence on external calls for funding — particularly evident in the hypoxia case — points to the need for more robust post-contract sustainability strategies. While securing royalty-based funding through external calls is a promising pathway, the ICT must develop mechanisms to autonomously reinvest these resources without relying exclusively on discretionary funding cycles. The hypoxia line's progression from TRL 4 to TRL 7–8 depends on resources from royalty agreements and partnerships with civil aviation companies - funding arrangements that are structurally less stable than the internal operational demand pull observed in the AGSM case. This asymmetry has implications for the strategic management of the SDPI's research portfolio: a balance between operationally driven projects (lower risk, lower innovation distance) and externally funded dual-use projects (higher risk, higher potential social return) is necessary for institutional resilience.

Second, the lack of direct economic impact indicators limits the ability to demonstrate to senior decision-makers the return on investment in the ICT model. The current metrics are predominantly output-based (articles, theses, and completed technological products). While these metrics are appropriate for academic evaluation, they do not capture outcomes such as reduced G-LOC incident rates, increased pilot career longevity, or cost savings resulting from reduced reliance on international training programs. Developing such indicators would strengthen the institutional case for continued investment in the ICT model and align the IMAE's evaluation framework with the public sector innovation literature, which emphasizes the measurement of public value creation (Bloch & Bugge, 2013).

Third, maintaining compliance with SINAER's evolving regulatory framework including NSCA 80 – 1/2024, NSCA 80 – 2/2019, and NSCA 80 – 10/2024 - amid growing demand for R&D partnerships will require sustained investment in personnel training and infrastructure upgrades. The model's success generates pressure for expansion, which must be managed sustainably. Given its limited dedicated staff, the SDPI may face capacity constraints as the portfolio of active projects grows.

Lessons for Military Health ICTs and Transferability

The IMAE experience offers lessons that, while shaped by the specific context of aerospace medicine and the SINAER framework, have potential applicability to other military health organizations within the Brazilian Armed Forces - including those in the Army and Navy, which operate under similar institutional arrangements in which multiple STIs share a single centralized NIT (Neves et al., 2026).

Three characteristics limit direct replicability: the technical specificity of aerospace medicine, which demands high-cost laboratory infrastructure (centrifuge, hypobaric chamber); the volume of operational demand generated by an air force with active fighter aviation; and the concentration of specialized

intellectual capital in a small number of national centers. However, four lessons emerge with broader applicability.

First, translational research as operational risk management. The IMAE model demonstrates that structuring research programs that directly connect academic investigation to operational training reduces vulnerability arising from dependence on foreign sources and strengthens technological autonomy. This is particularly relevant for military health areas in which commercial solutions are scarce or not adapted to operational requirements.

Second, the relationship between academic output and technological maturity. The structured TRL progression observed in the AGSM case - where articles and theses helped de-risk each subsequent stage of technological development - offers a replicable blueprint for ICTs seeking to consolidate their innovation ecosystem. This finding suggests that academic productivity metrics, often dismissed as disconnected from technological innovation, can serve as milestones in the maturation cycle when properly aligned with a technological roadmap.

Third, the importance of the centralized NIT as an enabler. The CGI/DCTA's role in providing legal certainty and strategic support was critical in enabling IMAE to focus on its technical mission without being overwhelmed by administrative complexity. As Neves et al. (2026) emphasize, this intermediation function — particularly the translation of research demands into legally viable partnership projects — is a core competency that distinguishes effective NITs from merely procedural ones.

Fourth, dual use as a social return multiplier. The normobaric hypoxia case illustrates that military health laboratory infrastructure can generate public value beyond the barracks. Institutionalizing mechanisms for dual-use technology transfer — including clear IP-sharing frameworks and simplified licensing pathways for civilian applications — would amplify the social return on defense R&D investment.

Conclusion

This study set out to investigate what institutional factors enabled the Institute of Aerospace Medicine (IMAE) — a military health organization operating within the Brazilian Aeronautics Innovation System (SINAER) — to convert academic research into operational products, and to examine what evidence indicates that this conversion capacity reflects institutional maturity as a Science and Technology Institution. The evidence from the document analysis of the 2022–2026 period, examined through the lenses of absorptive capacity, the valley of death, and the entrepreneurial state, supports three principal conclusions.

First, the evidence from the two embedded cases indicates that the IMAE has developed the institutional capacity characteristic of institutional maturity as an ICT - including the ability to structure R&D partnerships in compliance with SINAER, manage intellectual property assets under the ITP regime, capture extra-budgetary resources, and convert academic research into operational products across multiple technology readiness levels.

The Research and Innovation Subdivision (SDPI) functioned as a coordination hub that integrated the triple helix — government, academia, and industry — in the specific context of defense. The 15 technology and knowledge products documented (13 completed, 2 in progress) represent a level of output that, while modest in absolute terms, is significant for a military health organization that had no formal ICT structure four years prior.

Second, the IMAE successfully crossed the "valley of death" between academic research and operational application in at least one of the two examined cases. The Anti-G Straining Maneuver with muscular biofeedback reached Technology Readiness Level 8–9 and was implemented in the Physiological Adaptation Course (EAF) of the Brazilian Air Force, demonstrating the complete innovation cycle from basic electromyographic research to operational training. The hypoxia research line, while at an earlier stage of technological maturity (TRL 5–6), has advanced significantly through the development of normobaric protocols and the securing of external funding, with prospects for technology transfer to civil aviation — illustrating the dual-use potential of military health technologies.

Third, the SINAER normative and organizational framework provided the institutional conditions necessary, for this consolidation. The DCTA's role as the centralized NIT, the guidelines established by NSCA 80 – 1/2024 and NSCA 80 – 2/2019, and the IP protection mechanisms established by NSCA 80 – 10/2024 collectively created an environment in which a military health ICT could focus on its technical mission while the administrative and legal complexities of innovation partnerships were managed at the SINAER system level. This finding complements the work of Neves et al. (2026), who demonstrated the effectiveness of the SINAER governance model for technology transfer processes, and extends them to the specific domain of military health innovation — a field that remains underexplored in the Brazilian innovation literature.

Four limitations delimit the scope of these conclusions. First, the single-case design restricts external validity; the findings are analytically generalizable to the theoretical propositions of defense innovation systems rather than statistically generalizable to a population of military ICTs. Second, the available indicators are predominantly output-based (articles, theses, products), lacking direct economic impact metrics such as cost savings resulting from a reduction in accidents or return on R&D investment. Third, the researchers' positionality as members of the Brazilian Air Force introduces potential interpretive bias, which was managed through systematic triangulation but cannot be eliminated. These limitations, however, point to directions for future investigation.

Fourth, the study's research question was refined during the analysis to align with the scope of the available evidence. The findings address the institutional factors enabling research-to-operations conversion rather than the organizational transition process itself. Future research employing interviews with decision-makers and archival analysis of internal directives would be necessary to reconstruct the organization's transition trajectory.

Future research should pursue four lines of inquiry: (a) develop economic and operational impact indicators for IMAE's technological products, including G-LOC incident rates before and after the AGSM

biofeedback implementation and a comparative cost analysis with international training programs; (b) conduct a comparative analysis with military health ICTs in the other branches of the Brazilian Armed Forces (Army, Navy) and analogous organizations in other countries, to assess the replicability of the SINAER model; (c) investigate the specific contribution of the military chain of command, as distinct from that of the systemic governance design, to accelerating innovation cycles - observed in the AGSM case; and (d) evaluate the impact of ITP protocol formalization on the speed, security, and scope of R&D partnerships, particularly for dual-use technologies with civilian applications.

The provided enabling institutional conditions IMAE experience serves as a reference model for innovation management within military health ICTs in Brazil, demonstrating how organizations whose primary mission is the delivery of operational healthcare services can, when supported by an appropriate regulatory and organizational framework, convert scientific expertise into technological products that strengthen national sovereignty, optimize public resources, and enhance flight safety. The challenge that remains — and that this study has only begun to address — is to translate these institutional achievements into a model that can be systematically replicated for other military health organizations in the country.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

J.B. conceived the study, designed the methodology, conducted the document analysis and normative triangulation, interpreted the results, and wrote the main manuscript text. C.B. and G.L. contributed to the theoretical framework, reviewed the literature, and revised the manuscript critically for intellectual content. A.C. and B.L. reviewed the manuscript and provided critical revisions. All authors reviewed and approved the final version of the manuscript.

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