

MEDICAL DEVICE MAINTENANCE AND LOCAL CAPACITY: A COMPARATIVE STUDY OF SENEGAL AND CAMBODIA

Tapsoba Wendinmi Abdoul Kader¹

Iradukunda Sengesho Benigne²

Nizeyimana Jean Baptiste³

1. Joint Reseacher at Lisala University and UNCR University, Biomedical Engineering, Faculty of Engineering
2. Joint MPhil Researcher at Lisala University and UNCR University, IT Department, Film and TV Production
3. Lecturer at Lisala University, Faculty of Psychology and Education, Department of Technopedagogy

ABSTRACT

Achieving SDG 3 (Good Health and Well-Being) requires ensuring healthy lives and promoting well-being for all at all ages. Target 3.8 calls for achieving universal health coverage, including access to quality essential health-care services and access to safe, effective, quality, and affordable essential medicines and vaccines for all. Medical devices, ranging from simple thermometers and stethoscopes to sophisticated imaging equipment, ventilators, infusion pumps, and surgical instruments, are essential for diagnosis, treatment, monitoring, and rehabilitation. However, in low- and middle-income countries, medical devices frequently remain non-functional after donation or purchase due to lack of maintenance capacity, including insufficient trained

¹ Joint Reseacher at Lisala University and UNCR University, Biomedical Engineering, Faculty of Engineering

biomedical engineers and technicians, shortage of spare parts, unreliable electricity, harsh environmental conditions, weak supply chains, and poor equipment management systems.

This study conducts a comparative analysis of medical device maintenance and local capacity in Senegal and Cambodia, two low-income and lower-middle-income countries with contrasting geography, health system structures, and biomedical engineering development trajectories. Senegal has made significant investments in health infrastructure and medical equipment, often through donations and development partner support, but maintenance gaps persist, with an estimated 70 percent of medical devices non-functional. Cambodia has also expanded health infrastructure after decades of conflict, but medical device maintenance capacity is weak, with an estimated 60 to 70 percent of medical devices non-functional and fewer than 50 trained biomedical engineers nationally.

Using a qualitative comparative case study methodology, the study analyzes secondary data from government reports, WHO Global Atlas of Medical Devices, medical device assessments, peer-reviewed literature, and program evaluations over the period 2000 to 2025. The study finds that both countries face common challenges: a high proportion of non-functional devices, shortage of biomedical engineers and technicians, weak spare parts supply chains, donation management problems, and low political priority. Senegal has a national maintenance programme and a biomedical engineering school producing engineers, while Cambodia has fewer engineers but has benefited from targeted NGO and donor programs.

The study concludes that medical device maintenance requires systemic solutions, including national biomedical engineering workforce planning, pre-service and in-service training, spare parts supply chain development, preventive maintenance, computerized maintenance management systems, and donation management following WHO guidelines. Recommendations for both countries and the international community are provided.

Keywords: Medical device maintenance; local capacity; Senegal; Cambodia; SDG 3; biomedical engineering; health technology management

RÉSUMÉ

Atteindre l'ODD 3 (Bonne santé et bien-être) nécessite l'accès à des services de santé essentiels de qualité. Les dispositifs médicaux sont essentiels pour le diagnostic, le traitement, la surveillance et la réadaptation. Cependant, dans les pays à revenu faible ou intermédiaire, les dispositifs médicaux restent souvent non fonctionnels après leur don ou leur achat en raison d'un manque de capacité de maintenance. Cette étude analyse la maintenance des dispositifs médicaux et la capacité locale au Sénégal et au Cambodge. Les deux pays connaissent des défis similaires : 60 à 70 pour cent des dispositifs non fonctionnels, pénurie d'ingénieurs biomédicaux et de techniciens, chaînes d'approvisionnement de pièces de rechange faibles, problèmes de gestion des dons. Le Sénégal dispose d'un programme national de maintenance (PNMEH) et d'une école d'ingénieurs biomédicaux (ESIB). Le Cambodge compte moins d'ingénieurs, mais a bénéficié de programmes ciblés des donateurs (JICA, KOICA, OMS). L'étude conclut que la maintenance nécessite des solutions systémiques. Des recommandations sont fournies pour les deux pays et la communauté internationale.

Mots-clés : maintenance des dispositifs médicaux, capacité locale, Sénégal, Cambodge, ODD 3, ingénierie biomédicale, gestion des technologies de la santé

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Auteurs correspondant : *Tapsoba Wendinmi Abdoul Kader, Iradukunda Sengesho Benigne and Nizeyimana Jean*

Adresses électroniques : *tapsobawendinmiabdoulkader@cirep.ac.cd, benigneira0@gmail.com,*

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1. INTRODUCTION

Achieving SDG 3 (Good Health and Well-Being) requires ensuring healthy lives and promoting well-being for all at all ages. Target 3.8 calls for achieving universal health coverage, including access to quality essential health-care services and access to safe, effective, quality, and affordable essential medicines and vaccines for all.

Medical devices, ranging from simple thermometers and stethoscopes to sophisticated imaging equipment (X-ray, CT, MRI), ventilators, infusion pumps, surgical instruments, laboratory

analyzers, anesthesia machines, patient monitors, and implants, are essential for diagnosis, treatment, monitoring, and rehabilitation. Without functional medical devices, health systems cannot deliver quality care. A hospital without a functioning X-ray machine cannot diagnose fractures, tuberculosis, or pneumonia. Without a ventilator, it cannot support COVID-19 or surgical patients. Without a patient monitor, it cannot track vital signs during anesthesia. Without an incubator, it cannot care for premature newborns.

In low- and middle-income countries (LMICs), medical devices frequently remain non-functional after donation or purchase due to lack of maintenance capacity. The World Health Organization recommends one biomedical engineer per 100 hospital beds and one technician per 50 beds. Many LMICs have one engineer per 1,000 to 5,000 beds. Other challenges include shortage of spare parts due to import delays and high costs, unreliable electricity with voltage fluctuations that damage sensitive electronics, harsh environmental conditions including heat, humidity, and dust, weak supply chains with no local distributors and long lead times, poor equipment management systems with no inventory, no maintenance schedules, and no tracking, and lack of political priority, where budgets for maintenance are often zero while budgets for equipment purchase are available.

This study examines two countries that offer profound insights into medical device maintenance and local capacity: Senegal and Cambodia.

Senegal, a West African country with a population of 17 million and a GDP per capita of \$1,600, is classified as lower-middle-income. Senegal has made significant investments in health infrastructure, including regional hospitals, district health centers, and primary health posts, and in medical equipment, often through donations and development partner support from the Global Fund for HIV, TB, and Malaria, the World Bank, China, France, the European Union, and the Islamic Development Bank. However, maintenance gaps persist. Studies estimate that up to 70 percent of medical devices in public hospitals are non-functional. Contributing factors include a shortage of biomedical engineers and technicians, weak spare parts supply chains, and poor donation management.

Senegal has established a national maintenance programme, known as PNMEH (Programme National de Maintenance des Equipements Hospitaliers), and a biomedical engineering school, known as ESIB (Ecole Supérieure d'Ingénieurs Biomédicaux) at Université Cheikh Anta Diop in Dakar, which produces 20 to 30 engineers annually. The country also has regional maintenance units called UTM (Unités Techniques de Maintenance) in several cities. However, challenges remain, including underfunding of the maintenance programme, limited technician training, and slow spare parts procurement.

Cambodia, a Southeast Asian country with a population of 17 million and a GDP per capita of \$1,800, is also classified as lower-middle-income. Cambodia has expanded its health infrastructure after decades of conflict. The Khmer Rouge regime from 1975 to 1979 destroyed the health system, killed an estimated 90 percent of physicians, and destroyed medical equipment, often using it as scrap metal. Post-conflict reconstruction from the 1990s to the 2020s rebuilt health infrastructure with donor support from the World Health Organization, the World Bank, the Asian Development Bank, JICA (Japan International Cooperation Agency), KOICA (Korea International Cooperation Agency), China, and the European Union.

However, medical device maintenance capacity remains weak. An estimated 60 to 70 percent of medical devices are non-functional. The biomedical engineering workforce is tiny, with fewer than 50 trained biomedical engineers nationally, mostly concentrated in the capital city of Phnom Penh. Spare parts are imported with long lead times of three to six months, high costs, and customs delays. Preventive maintenance is minimal, with no schedule and no budget. Donation management is problematic, with devices donated without needs assessment, resulting in incompatibility with local conditions such as voltage, language, and consumables, and with no training, no spare parts, and no maintenance plan.

Cambodia has taken several initiatives. A biomedical engineering curriculum has been developed at the Institute of Technology of Cambodia (ITC) and at the University of Health Sciences (UHS) in Phnom Penh. The WHO-supported Health Technology Management (HTM) program has provided training, assessments, and pilot maintenance units. Some hospitals have biomedical maintenance units funded by NGOs such as Friends without a Border at Angkor Hospital for Children in Siem Reap and the Children's Surgical Centre in Phnom Penh. Development partners

including JICA (maintenance training), KOICA (hospital equipment support with maintenance contracts), and China (hospital construction and equipment donation) have contributed. Regional maintenance hubs have been piloted in Siem Reap and Battambang. However, challenges remain, including low political priority for biomedical engineering, retention of trained staff who leave for the private sector or overseas, and lack of a regulatory framework for medical device donation and procurement, with no quality assurance, no pre-market approval, and no post-market surveillance.

The contrast between Senegal and Cambodia illuminates critical questions for medical device maintenance, local capacity, and SDG 3, which this study addresses.

2. LITERATURE REVIEW

The literature on medical device maintenance in low- and middle-income countries is substantial and growing. The World Health Organization has published several key documents, including the Global Atlas of Medical Devices (2020), barriers to innovation in the field of medical devices (2010), guidelines for medical device donations (2011), and human resources for medical devices (2017). The World Health Assembly has adopted resolutions WHA60.29 (2007) on health technologies and WHA71.13 (2018) on medical devices, calling on member states to develop national policies for health technology management.

The scale of the problem is well documented. Studies consistently report that 50 to 80 percent of medical devices in low- and middle-income countries are non-functional. The WHO donation guidelines (2011) are widely cited but poorly implemented. The PATH organization has published assessments of medical device maintenance in low-resource settings (2015, 2018), highlighting common challenges including workforce shortages, spare parts gaps, and donation management failures.

Country-specific studies on Senegal are available. PNMEH reports provide data on maintenance activities and challenges. Diop et al. (2015) documented the state of medical device maintenance in Senegal, noting that 70 percent of devices are non-functional and that workforce shortages are severe. Sarr et al. (2018) analyzed the biomedical engineering workforce in Senegal, highlighting the role of ESIB in training engineers and the need for more technicians. ESIB theses and reports provide additional insights.

Country-specific studies on Cambodia are more limited but growing. WHO Cambodia HTM reports (2020) document the Health Technology Management program, including assessments, training, and pilot maintenance hubs. JICA evaluation reports (2018) assess the impact of maintenance training programs. KOICA reports describe hospital equipment support. YENOK (2016) documented medical equipment maintenance challenges in Cambodia. These sources consistently identify low workforce capacity, donor dependence, and lack of a national maintenance programme as key barriers.

Comparative studies across Senegal and Cambodia are rare. Most studies focus on either African or Asian contexts separately. This study fills that gap by providing a structured comparison of medical device maintenance and local capacity in Senegal and Cambodia.

3. RESEARCH QUESTIONS

This study addresses the following research questions:

1. What is the state of medical device maintenance and local capacity in Senegal and Cambodia, including non-functional rates, workforce, spare parts, and donation management?
2. What policies, programmes, and institutions exist in each country, including PNMEH, ESIB, and WHO HTM?
3. What are the outcomes of these policies and programmes in terms of functional devices, trained graduates, and maintenance coverage?
4. What can each country learn from the other about improving medical device maintenance and local capacity?

4. METHODOLOGY

This study employs a qualitative comparative case study methodology to examine medical device maintenance and local capacity in Senegal and Cambodia. The comparative approach is appropriate for examining how different historical, political, and institutional contexts shape maintenance outcomes.

Senegal and Cambodia were selected as cases offering meaningful comparison. Both countries are lower-middle-income with populations of approximately 17 million and GDP per capita

between 1,600 and 1,800. Both were former French colonies, with Senegal becoming independent in 1960 and Cambodia a French protectorate from 1863 to 1953. Both have similar tropical climates. However, they differ in region, with Senegal in West Africa and Cambodia in Southeast Asia, and in conflict history, with Senegal experiencing low-intensity conflict in the Casamance region while Cambodia experienced the Khmer Rouge genocide from 1975 to 1979, which destroyed its health system.

The research design integrates secondary analysis of multiple data sources spanning the period 2000 to 2025. Government sources include, for Senegal, the Ministry of Health and Social Action, PNMEH reports, ESIB reports, and UTM reports; for Cambodia, the Ministry of Health, the Department of Hospital Services, ITC, and UHS. International databases include the WHO Global Atlas of Medical Devices. Program evaluations include PATH assessments, JICA evaluation reports, and KOICA reports. Peer-reviewed literature is also analyzed.

The analytical framework examines five dimensions: workforce (biomedical engineers, technicians), infrastructure (maintenance units, test equipment, spare parts), policies (donation guidelines, procurement regulations), training (pre-service and in-service programs), and outcomes (functional devices, maintenance coverage).

The study has several limitations, including reliance on secondary data constrained by availability, quality, and comparability. Data from Senegal are limited in some areas, and data from Cambodia have gaps due to the destruction of records during the Khmer Rouge period. The comparative case study design cannot establish causality as rigorously as experimental methods. No primary data collection was conducted. The study period does not fully explore longer-term historical dynamics. Despite these limitations, the comparative analysis provides valuable insights for policy and future research.

5.

RESULTS

Table 1: Comparative Summary – Medical Device Maintenance

Dimension	Senegal	Cambodia
Population (2024)	17 million	17 million

GDP per capita (USD)	\$1,600 (lower-middle)	\$1,800 (lower-middle)
Health expenditure per capita (USD)	\$60	\$80
Estimated non-functional medical devices (public hospitals)	70%	60-70%
Biomedical engineers (national)	~200 (ESIB graduates 20-30/year since 2009)	<50 (ITC, UHS)
Biomedical technicians (mid-level)	~300 (limited 2-year programs)	~100-200 (on-the-job trained, few formal)
Ratio biomedical engineers per 100 hospital beds	~0.2 (1 per 500 beds) vs WHO recommendation 1 per 100	~0.1 (1 per 1,000 beds)
National maintenance programme	PNMEH (Programme National de Maintenance des Equipements Hospitaliers) – since 2005	None (pilot WHO HTM)
Biomedical engineering school	ESIB (UCAD, Dakar) – since 2009, 5-year engineering degree, 20-30 graduates/year	ITC (biomedical engineering option), UHS (medical technology) – limited capacity
Regional maintenance units	UTMs (Unités Techniques de Maintenance) – Saint-Louis, Thiès, Kaolack, Ziguinchor, Tambacounda	Pilot hubs: Siem Reap, Battambang (WHO HTM)
Spare parts availability	Weak (customs delays, no local manufacturing)	Very weak (import only, 3-6 months lead time)
Donation management policy	PNMEH coordinates; weak enforcement	None (ad hoc)
Computerized maintenance management system (CMMS)	Pilot (not scaled)	None

Source	PNMEH 2022; ESIB 2023; Diop et al. 2015	MOH Cambodia 2021; WHO HTM 2020; JICA 2018
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Table 2: Senegal – Medical Device Maintenance System

Element	Description
PNMEH (Programme National de Maintenance des Equipements Hospitaliers)	Established 2005, under Ministry of Health (Direction de la Pharmacie, du Médicament et des Laboratoires – DPML, now Direction de l’Equipe-ment). Mandate: coordinate maintenance for public hospitals (national, regional, district). Activities: inventory medical devices (partial), organize preventive maintenance (limited), manage spare parts procurement, contract external service providers (for specialized equipment – CT, MRI, linear accelerators), train hospital maintenance staff. Budget: underfunded (only operational costs, not spare parts).
ESIB (Ecole Supérieure d’Ingénieurs Biomédicaux)	Faculty of Engineering Sciences, Université Cheikh Anta Diop (UCAD), Dakar. Founded 2009 (French cooperation). 5-year engineering degree (BAC+5). Curriculum: biomedical instrumentation, medical imaging, clinical engineering, hospital safety, maintenance management, signal processing, biomechanics, biomaterials, regulations. Graduates: 20-30/year. Employment: Ministry of Health (PNMEH, regional hospitals), private sector (medical device companies – Siemens, GE, Philips, Medtronic, local distributors), international organizations (WHO, UNDP).
Biomedical technicians (mid-level)	2-year degree (Brevet de Technicien Supérieur – BTS) in biomedical maintenance at technical schools (Lycée Technique de Thiès, others). Limited capacity (20-30 graduates/year). Many technicians trained on the job (no formal qualification). Critical shortage.
UTMs (Unités Techniques de Maintenance)	Decentralized maintenance units located in regional hospitals (Saint-Louis (North), Thiès (West), Kaolack (Central), Ziguinchor (South), Tambacounda (East)). Staff: 1-2 biomedical engineers, 2-4 technicians, support staff. Equipment: basic test equipment (multimeters, manometers, thermometers), but

	lack specialized tools (patient simulators, electrical safety analyzers, flow meters, ventilator testers). Spare parts: limited (no stock, order on failure).
Donation management	PNMEH coordinates but no enforcement. WHO donation guidelines (2011) not implemented. Common problems: donated devices incompatible (voltage 110V vs 220V, language (Chinese, Japanese manuals only), no consumables (test strips, reagents, electrodes), no training, no spare parts, no maintenance plan. Many donations fail within 6 months.
Computerized maintenance management system (CMMS)	Pilot (few hospitals) – not scaled. Paper-based maintenance logs lost, incomplete.
Challenges	High non-functional rate (70%). Workforce shortage (engineers, technicians). Spare parts supply chain (customs clearance 3-6 months, no local distributors for many brands). Low budget (0% of hospital budget for maintenance – WHO recommends 4-6% of equipment purchase price annually). Preventive maintenance not performed. Hospital management engagement low (biomedical engineers excluded from procurement decisions).

Table 3: Cambodia – Medical Device Maintenance System

Element	Description
Ministry of Health	Department of Hospital Services (DHS) oversees medical equipment. Directorate of Procurement and Logistics – procurement. No dedicated biomedical engineering department at central level.
Biomedical engineering workforce	<50 trained biomedical engineers. Most in Phnom Penh: Ministry of Health (technical advisors), Calmette Hospital (national referral), Khmer-Soviet Friendship Hospital (now Russian? – Russian Friendship Hospital), National Pediatric Hospital, Kantha Bopha Hospitals (Swiss-funded, Swiss engineers, but not Khmer). Few engineers in provinces (Siem Reap, Battambang, Kampong Cham). Technicians: 100-200 (on-the-job trained, many from electronics background, not biomedical specific).

Training programs	Institute of Technology of Cambodia (ITC, Phnom Penh) – biomedical engineering option (within Electrical Engineering department, 15-20 graduates/year). University of Health Sciences (UHS) – medical technology (associate degree). No dedicated biomedical engineering school.
WHO Health Technology Management (HTM) program	WHO Cambodia supported (2015-2025). Activities: assessment of medical device needs, training of biomedical engineers and technicians (train-the-trainer), development of maintenance guidelines, pilot regional maintenance hubs (Siem Reap Provincial Hospital, Battambang Provincial Hospital), donation management guidelines, CMMS pilot.
Donor programs	JICA (Japan International Cooperation Agency): maintenance training for hospital engineers (2000s-2010s), spare parts supply support. KOICA (Korea International Cooperation Agency): hospital equipment donation (X-ray, ultrasound, lab analyzers) + maintenance contract (limited duration – 3-5 years). China: hospital construction (Chinese Friendship Hospitals) + equipment donation (Chinese brands) – but manuals in Chinese, no spare parts, no training, no maintenance plan. WHO: HTM program. Global Fund: equipment for TB, malaria, HIV (microscopes, geneXpert, CD4 analyzers) – includes maintenance contract? Variable.
NGO support	Friends without a Border (Angkor Hospital for Children, Siem Reap) – biomedical department (5+ engineers, well-equipped, maintains own equipment). Children's Surgical Centre (Phnom Penh) – biomedical technician. Both provide training to MOH hospital staff.
Spare parts	Import only (no local manufacturing, few local distributors). Lead time 3-6 months (order from Singapore, Thailand, China, Japan, Korea, Europe). Customs duties (though exemptions for health equipment, but bureaucratic delays). Consignment stock: none.
Donation management	No policy. WHO donation guidelines not implemented. Hospitals accept any donation regardless of need, compatibility. Donations often fail.
Challenges	Political priority low (budget for maintenance <1% of hospital budget). Workforce critical shortage (<50 engineers, 100-200 technicians for 100+ hospitals). Retention:

	trained engineers leave for private sector (medical device companies offer 3-5x salary), overseas (Singapore, Thailand, Malaysia, Japan, Korea, Australia). Spare parts supply chain broken. No national maintenance programme (unlike Senegal's PNMEH). No biomedical engineering department at Ministry of Health. No regulatory authority for medical devices (no quality assurance, no pre-market approval, no post-market surveillance, no registration).
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Table 4: Comparative Training and Workforce

Indicator	Senegal	Cambodia
Biomedical engineering school (5-year)	ESIB (UCAD) – 20-30/year	None (ITC biomedical engineering option – 15-20/year, 4-year?)
Technician (2-3 year) program	BTS at Lycée Technique de Thiès (20-30/year)	UHS medical technology (limited)
Total biomedical engineers (national)	~200	<50
Total biomedical technicians	~300	~100-200
Annual graduates (engineers + technicians)	40-60	20-30
Target workforce (engineers + technicians for 17M population, 100+ hospitals)	1,000+	1,000+
Years to reach target at current rate	15-20 years	30-40 years
Retention	Moderate (public sector salary low, but better than Cambodia)	Very low (brain drain to private sector, overseas)
Foreign training	France (AFIB, French cooperation), some masters abroad	JICA (Japan), KOICA (Korea), Australia, China
Source	ESIB 2023; Diop et al. 2015	ITC 2023; WHO HTM 2020

6. DISCUSSION OF RESULTS

6.1. Explaining the High Non-Functional Device Rate in Both Countries

Both Senegal and Cambodia have non-functional medical device rates of 60 to 70 percent. Common causes include:

- Workforce shortage: Biomedical engineers are at 0.2 per 100 beds in Senegal and 0.1 per 100 beds in Cambodia, compared to the WHO recommendation of 1 per 100 beds.
- Spare parts unavailability: Import delays, customs clearance problems, no local distributors, and no consignment stock.
- Preventive maintenance not performed: No schedule, no budget, and no staff.
- Inadequate training: Operators such as nurses and clinicians misuse or damage devices.
- Harsh environment: Heat, humidity, dust, and power surges damage equipment.
- Donation management failure: Inappropriate devices, no training, no spare parts.
- Weak hospital management: Biomedical engineers are excluded from procurement and budget decisions.

6.2. Senegal's PNMEH: Strength and Weakness

Senegal's PNMEH (National Maintenance Programme) is a strength. It provides central coordination, regional maintenance units (UTMs), training support, and centralized spare parts procurement. However, PNMEH is underfunded. The budget covers salaries only, not spare parts, not test equipment, and not training. The UTMs lack specialized test equipment such as patient simulators, electrical safety analyzers, and ventilator testers. Spare parts procurement remains slow, with customs clearance taking three to six months. PNMEH's mandate is coordination, not direct execution, and hospitals must budget for maintenance themselves, but most do not.

6.3. Cambodia's Workforce Crisis

Cambodia's biomedical engineering workforce is critically underdeveloped, with fewer than 50 engineers. The Khmer Rouge genocide destroyed the health system and killed educated

professionals. Post-conflict reconstruction prioritized physicians, nurses, and administrators, not biomedical engineers. Training programs at ITC produce only 15 to 20 graduates per year, which is insufficient. Retention is very poor, as trained staff leave for the private sector or overseas.

Cambodia needs a National Biomedical Engineering Workforce Plan targeting 200 engineers and 500 technicians by 2030, which would take 10 to 15 years. This would require expanding training programs at ITC, UHS, and regional training centers, and providing scholarships, rural service schemes, and retention incentives.

6.4. Donation Management: A Recurring Problem

Both countries lack effective donation management. Senegal's PNMEH coordinates but cannot refuse donations due to political pressure. Cambodia has no policy at all. The WHO Medical Device Donation Guidelines (2011) specify that donations should be based on needs assessment, ensure compatibility (voltage, language, consumables, climate), include training, spare parts, and a maintenance plan, and include pre-donation evaluation and post-donation follow-up. Neither country implements these guidelines. Many donations fail within six months.

Recommendations: The Ministry of Health must establish a donation approval committee including biomedical engineers, clinicians, and hospital administrators. WHO guidelines must be applied. Inappropriate donations must be refused. Donated devices must be tracked using a CMMS.

6.5. Spare Parts Supply Chain

Both countries face a common challenge with spare parts. Local distributors for major brands (Siemens, GE, Philips, Mindray) exist in the capital cities of Dakar and Phnom Penh but not nationwide. Consignment stock, where spare parts are held at the distributor and paid for when used, could reduce lead time. Group purchasing, where multiple hospitals pool orders, could reduce costs. Local manufacturing of simple parts such as cables, holders, and batteries could be developed, and 3D printing of plastic components could be explored.

6.6. Preventive Maintenance and CMMS

Preventive maintenance reduces breakdowns by 50 to 70 percent, extends device life, and reduces costs. Neither country has systematic preventive maintenance. Preventive maintenance requires a schedule (daily, weekly, monthly, quarterly, annual), checklists, trained staff, test equipment, spare parts, and budget. A CMMS (computerized maintenance management system) tracks devices, maintenance history, schedules, spare parts inventory, and costs. Senegal has a pilot CMMS that has not been scaled. Cambodia has none. International donors should fund CMMS implementation, and open-source options are available.

6.7. Transferability: What Senegal Can Learn from Cambodia and What Cambodia Can Learn from Senegal

Senegal can learn from Cambodia in several areas:

- The WHO HTM program in Cambodia demonstrates effective collaboration with WHO on assessments, training, and pilot maintenance hubs. Senegal could strengthen collaboration with WHO AFRO and WHO Senegal to replicate this approach.
- Cambodia's use of local NGOs for biomedical maintenance (Friends without a Border, Children's Surgical Centre) could inspire Senegal to engage local NGOs, the private sector, and religious hospitals.
- Cambodia's experience with JICA training from Japan could encourage Senegal to seek bilateral training partnerships with France, Germany, Japan, and China.

Cambodia can learn from Senegal in several areas:

- Senegal's national maintenance programme (PNMEH) provides a model. Cambodia should establish a similar central unit within the Ministry of Health, such as a Department of Biomedical Engineering.
- Senegal's biomedical engineering school (ESIB) provides a model. Cambodia should establish a dedicated 5-year biomedical engineering school rather than only an option within electrical engineering.
- Senegal's regional maintenance units (UTMs) provide a model. Cambodia should create decentralized maintenance hubs in Siem Reap, Battambang, Kampong Cham, Takeo, and other provinces.

6.8. Implications for SDG 3

Medical device maintenance is essential for SDG Target 3.8 (universal health coverage and quality health services). Without functional medical devices, hospitals cannot provide quality care. Diagnoses are missed, treatments fail, and surgical complications rise. The WHO estimates that 50 to 80 percent of medical devices in low- and middle-income countries are non-functional, representing billions of dollars in wasted investment.

The international community, including WHO, the World Bank, the Global Fund, Gavi, and bilateral donors, should require maintenance plans as a condition of equipment donation, applying WHO guidelines. They should fund biomedical engineering workforce development through scholarships, training programs, and retention incentives. They should support spare parts supply chains through local distributors, consignment stock, and group purchasing. They should implement CMMS and create regional maintenance hubs. They should promote South-South exchange among Senegal, Cambodia, Ivory Coast, Rwanda, and Vietnam.

7. CONCLUSION

This comparative analysis reveals that medical device maintenance and local capacity in Senegal and Cambodia face common challenges but offer different institutional responses.

Senegal has a national maintenance programme (PNMEH, 2005), a biomedical engineering school (ESIB, 2009, producing 20 to 30 engineers per year), and regional maintenance units (UTMs). However, it still suffers from a 70 percent non-functional device rate due to workforce shortages, spare parts gaps, underfunding, and weak donation management.

Cambodia has fewer biomedical engineers (fewer than 50), no national maintenance programme, and a very weak spare parts supply chain. However, it has benefited from the WHO Health Technology Management program, NGO support (Friends without a Border), and donor training (JICA, KOICA). The non-functional device rate is 60 to 70 percent.

Several cross-cutting insights emerge from this comparison:

1. Workforce is the foundation. Biomedical engineers and technicians are essential, yet both countries produce far fewer than needed. Senegal produces 40 to 60 graduates per year, and Cambodia produces 20 to 30 per year, while both need more than 1,000.
2. National maintenance programmes like Senegal's PNMEH provide coordination but require adequate funding for spare parts, test equipment, and training.
3. Spare parts supply chains are broken, with import delays, high costs, and no local distributors.
4. Donation management fails due to inappropriate devices, no training, and no spare parts.
5. Preventive maintenance and CMMS are absent in both countries.

For Senegal, priorities include: scaling up technician training through 2-year BTS programs to produce 100 or more graduates per year; strengthening PNMEH with a budget increase of 10 times, performance monitoring, and spare parts stock; implementing CMMS for digital maintenance tracking; enforcing donation guidelines with Ministry approval; expanding UTMs to all 14 regions; and engaging the private sector for maintenance contracts for specialized equipment.

For Cambodia, priorities include: developing a National Biomedical Engineering Workforce Plan targeting 200 engineers and 500 technicians by 2030; establishing a dedicated biomedical engineering school offering a 5-year degree with 50 to 100 graduates per year; expanding ITC and UHS programs; creating a National Medical Device Regulatory Authority for registration, quality assurance, and post-market surveillance; establishing a national maintenance programme within the Ministry of Health; scaling up WHO HTM nationwide with regional hubs in all provinces; creating a spare parts consortium for group purchasing and local stock; and implementing WHO donation guidelines.

For the international community, the lessons are clear. Medical device donations without maintenance plans are waste. WHO donation guidelines must be enforced by both donors and recipients. Biomedical engineering workforce development must be funded through scholarships, training programs, and retention incentives. Spare parts supply chains need support through local distributors and consignment stock. CMMS should be standard.

The ultimate measure of success for medical device policy is not the number of devices purchased, but whether a ventilator in a rural Senegalese hospital and an X-ray machine in a Cambodian provincial hospital are functional when a patient needs them.

8. LIMITS OF THE STUDY

This study has several limitations. First, reliance on secondary data from government reports, WHO databases, and peer-reviewed literature means the analysis is constrained by data availability, quality, and comparability. Senegal's PNMEH reports are limited in detail, and Cambodia's data have gaps due to the destruction of records during the Khmer Rouge period. Second, the comparative case study design cannot establish causality as rigorously as experimental or quasi-experimental methods. Third, the study does not include primary data collection, such as hospital assessments or interviews with biomedical engineers, technicians, and hospital administrators, which would provide richer insights. Fourth, the study period (2000 to 2025) captures recent trends but does not fully explore longer-term historical dynamics, particularly the impact of the Khmer Rouge genocide on Cambodia's health system. Fifth, the focus on national-level systems obscures subnational variation within Senegal (Dakar versus rural regions) and within Cambodia (Phnom Penh versus provinces). Sixth, the study does not quantify the cost-effectiveness of different maintenance strategies. Despite these limitations, the comparative analysis provides valuable insights for policy and future research.

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10. AUTHOR CONTRIBUTIONS

TAPSOBA WENDINMI ABDOUL KADER conceived the study, designed the methodology, conducted the literature review and document analysis, synthesized findings, and drafted the complete manuscript.

11. COMPETING INTERESTS

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential competing interest.

12. FUNDING INFORMATION

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13. DATA AVAILABILITY

All sources are publicly available documents cited in the bibliography and accessible through the referenced publications and organizations, including PNMEH reports, ESIB, WHO Global Atlas of Medical Devices, PATH, JICA, and KOICA.

14. DISCLAIMER

The views expressed in this article are solely those of the author and do not necessarily reflect the views of any institution or organization with which the author may be affiliated. The analysis is provided for scholarly purposes and should not be construed as policy guidance or programmatic advice.

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