Challenges of microscopy technology dissemination to resource-constrained communities: a misstep or a missed step?

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Introduction

There is an unmistakable, palpable momentum in the global effort to disseminate modern microscopy technologies and expertise, especially to underserved scientific communities. This impetus is propelled largely by the timely confluence of several important factors. These include (i) the rapid development of low-cost, open-source microscopes enabled primarily by 3D-printing technologies, and the opportunity to piggy-back on the advances in consumer electronics, as well as increasing availability of affordable and high-performance optical components, (ii) powerful open-source software and the accelerating capabilities of machine learning to enhance the performance of even run-of-the-mill microscopes, and (iii) the increasing appreciation that technology distribution and access cannot continue to sideline research in under-resourced communities, in particular, the Global South where the frontline battles against many diseases and climate change impacts of global importance are waged.

With the attention of international funders progressively pivoting toward open access microscopy research infrastructure and local expertise enhancement[1], microscopy dissemination is a prominent topic in the global scientific dialogue. Although "technology sharing plans" are now commonly found as a mandatory section on most technology development grant applications, sharing is not the same as dissemination. By definition, technology development is only as successful as its ability to address an unmet need. In that regard, developers do not need further incentive to make their technology publicly available. A more important question is whether merely sharing a technology will translate into successful uptake and implementation. In fact, asking for a sharing plan will likely invite perfunctory promises of technology sharing that have little realistic chance of broad adoption. A technology can only reach its target adopters by recognizing and overcoming the numerous barriers that prevent its ultimate uptake[2]. This requires considerable investment, coordination, and effort to bring to fruition, as has been noted previously[1].

Research technology uptake in resource-limited environments must be deliberately fostered by a multi-pronged strategy. This includes (i) stimulating demand through creating awareness, (ii) building accessibility, (iii) developing local technical expertise and multidisciplinary team, (iv) incentivizing continued utilization of the technology for scientific output, (v) addressing local scientific and medical needs, and (vi) motivating governments of lower- and middle-income countries to lower regulatory-, visa-, and tax-related barriers to technology and capability sharing and to invest their own resources to develop local capability. Due to the interdependency of each ingredient in this recipe for success, failure to implement any one effectively can limit the ultimate impact and reach of the technology. To date, there have been numerous programs aimed at disseminating imaging technologies to resource-constrained regions. While necessary, dissemination alone is unfortunately insufficient to cement broad uptake of microscopy into the toolbox of resource-challenged scientists.

In May 2024, global imaging leaders held a conference titled "Microscopy Technology Dissemination to Underserved Communities" at the Janelia Research Campus of the Howard Hughes Medical Institute. During this meeting, the underlying problems hindering effective adoption of microscopy were examined from the perspectives of tool developers, imaging communities, publishers and funders alike. This white paper captures the conclusions from these discussions and outlines the necessary steps to bridge technology dissemination and the subsequent scientific output.

Microscopy Dissemination

Through a common purpose, imaging scientists and funders across the globe have built unprecedented momentum in microscopy technology dissemination over the past decade. These efforts, as outlined in Figure 1, form the necessary multi-pronged strategy for successful technology dissemination. For instance, the continued formation of regional and global imaging communities shows no sign of deceleration (Table 1). Microscopy workshops and even train-the-trainer programs are being offered at such a fast rate across the world that it is impossible to keep pace to provide a complete list. Capacity-building and open-access platforms, as exemplified by those listed in Table 1, continue to be created to provide national and continental accessibility to microscopy tools.

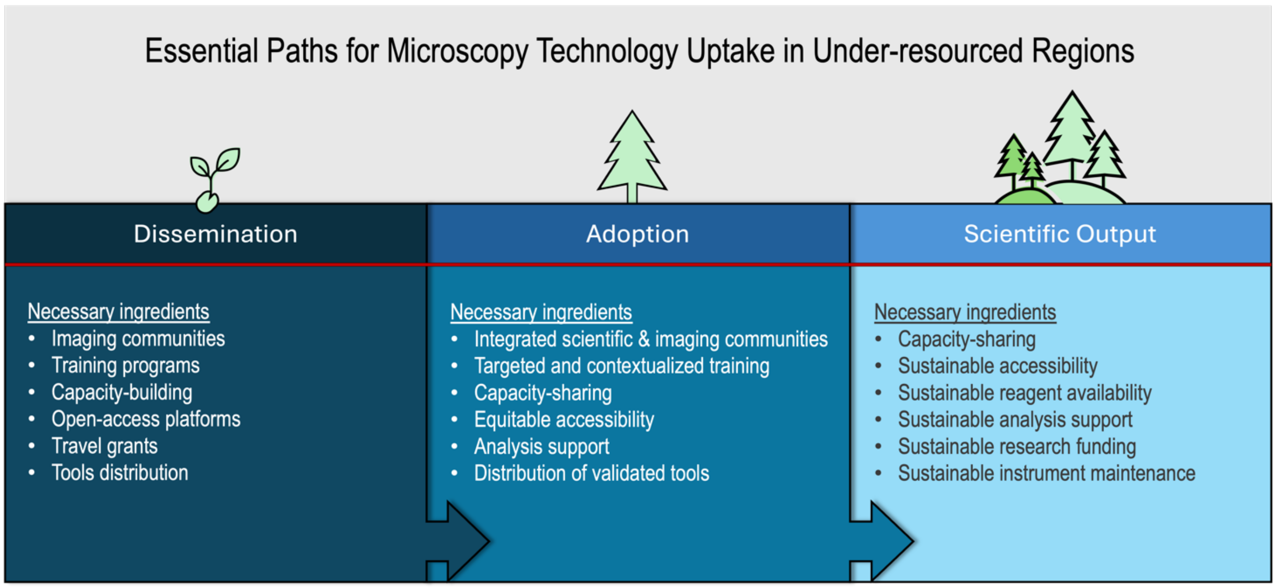

Figure 1 Technology uptake is a stepwise process that includes dissemination and adoption, leading to scientific output. While the underlying principles in the dissemination phase are similar to that in the adoption phase, there are key differences in the approach that are necessary to transition the disseminative groundwork to successful technology adoption. These changes in approach must also be sufficiently sustained in order to support scientific output.

While vital, open-access platforms still remain largely inaccessible to scientists in under-resourced regions. This gap, however, can be filled by dedicated exchange programs to build researchers' expertise, creative instrument distribution efforts[3] and the rapid advent of frugal microscopes that can be easily disseminated or locally manufactured[4–8]. These innovative solutions are further propelled by many open-source machine learning tools[9–11] designed to enhance the performance of optical instruments, even under sub-optimal conditions. But perhaps the most consequential effort of all is the formation of imaging networks across the globe, many of them self-tasked with the explicit mission of technology dissemination. These organizations (Table 1) have pioneered key initiatives toward developing imaging capacity, training opportunities, image analysis support, and community-building. In addition, they have further connected biologists with imaging centers regionally and globally through travel grants (Table 1).

Despite these investments and the resulting initial enthusiasm, many global efforts have struggled to produce the desired outcome of wider microscopy adoption in under-resourced scientific communities. Researchers in these communities are still experiencing important barriers that are slowing down their microscopy-driven discoveries[12]. It is important to recognize that there will always be a considerable time lag between technology adoption and scientific output, even under the best circumstances[13]. In fact, even the most promising technologies need to go through a period "teething pain", where appropriate pairing with biological applications, protocol development, and data handling pipelines have to occur[14]. However, these hurdles do not account for the apparent lack of microscopy technology uptake. In other words, we have not been able to successfully cross the finish line of technology adoption yet (Figure 1). This prompts the question of whether there has been a miscalculated step.

Table 1 Examples of various global microscopy dissemination efforts

Examples of microscopy platforms	Regional representation	
France BioImaging	National platform	france-bioimaging.org
Microscopy Australia	National platform	micro.org.au
SingaScope	National platform	singascope.sg
ABiS	National platform	nibb.ac.jp/abis/
Euro-Bioimaging	Continental platform	www.eurobioimaging.eu
Africa Microscopy Initiative	Continental platform	www.microscopy.africa

Examples of microscopy communities	Regional representation	
Quebec Bio-Imaging Network	Provincial network	rbiq-qbin.qc.ca
South Africa BioImaging	National network	www.sabioimaging.org
BioSee	Regional network	bio-see.net
Wambian	Regional network	www.wambian.org
African BioImaging Consortium	Continental network	www.africanbioimaging.org
Latin American BioImaging	Continental network	labi.lat
BioImaging North America	Continental networks	www.bioimagingnorthamerica.org
Global BioImaging	Global network of networks	globalbioimaging.org

Examples of opportunities	Support type	
Imaging Africa	Continental workshops	www.imagingafrica.org
SWIFT Awards	Continental microscopy access	www.africanbioimaging.org/swift
AMI Imaging Centre	Continental microscopy access	www.center.microscopy.africa
AMI PEER program	Continental microscope distribution	www.equipment.microscopy.africa
openScopes	Global dissemination of capability	www.openScopes.com

As we have previously discussed[3], the barriers to adoption arrayed against microscopy are numerous and enormous. In addition, the nature of these barriers varies widely across regions due to local governmental support for research. As a consequence, recent efforts to overcome these myriad barriers against dissemination have likewise varied in their emphasis on the ultimate goal: technology adoption to facilitate scientific output. The overt focus on dissemination first has meant that "adoption" and "scientific output" have hardly made it into the lexicon of cross-community strategic dialogues to date. In fact, the terms "adoption" and "scientific output" have not been clearly defined in the context of microscopy uptake. Here, we define "adoption" as the recognition by biologists of microscopy as an indispensable pillar in their research program, whereby imaging-centric approaches are well-incorporated into their research, and well-leveraged to address key scientific questions. On the other hand, microscopy-driven "scientific output" in resource-constrained settings must be defined in broader terms than the conventional bibliometric measurement. It should include (i) rigorous, peer-reviewed scientific discoveries enabled by microscopy, (ii) deployable, quantitative evaluations such as point-of-care diagnosis or rapid field sample assessment for agricultural, ecological and environmental work, and (iii) local adaptation and development of imaging capabilities to address local priorities. While also important, here we have excluded the adoption of microscopes for educational purposes and focus solely on research and field-work applications. These definitions and boundaries allow us to focus specifically on the root cause of – and solutions to – the lagging adoption rate of imaging techniques to enable impactful scientific output.

Microscopy Adoption

Role of microscopy trainers to contextualize teaching

The complexity of modern biological studies – which rely on a cadre of rapidly evolving technologies in molecular biology, biochemistry, genomics, flow cytometry, mass spectroscopy, proteomics, and others – requires most life scientists to be a versatile jack of all trades. This, however, can also limit their capacity to gain intimately familiarity with the full technical details and operational principles of modern, complex microscopes. Likewise, the explosive growth in the use of analytical software, including machine learning, in microscopy has further brought many life scientists to even less familiar territories. In recognition of these challenges, the number of in-person, virtual, guided and self-driven training programs around imaging and analysis, as well as auxiliary resources guiding researchers to such platforms has proliferated in recent years. Despite increased accessibility to microscopy training courses and instruments, the rate of technology adoption by resource-constrained scientists still remains disproportionately low.

What is often under-appreciated is that the appeal of microscopy to life scientists lies in its effectiveness in solving their experimental challenges. Yet, few training courses have endeavored to relate microscopy techniques to these experimental questions, opting instead to focus predominantly on theoretical instruction, including optical principles[15]. It is important to note that a training course that is not tailored for the target audience serves more to alienate the attendees than to inspire them to adopt the technology[15,16]. In order to effectively reveal the power of microscopy, training programs should always spotlight science over technology. Therefore, curricula should emphasize how biologically informative results can be attained through rational, quantitative microscopy-based experimental design[17], rather than obtuse optical physics-based lectures with little biological context that can distract and overwhelm the learners. Contextualization of the workshop curricula to underserved communities further demands that the tools being introduced to the attendees are topic-specific, locally relevant, and taught by local scientists wherever possible, as exemplified by the Imaging Africa satellite workshops[3].

Role of imaging communities to create integrated scientific networks

Various imaging communities have fostered strong alliances wherein exchange of experience, expertise, tools, best practices and training curricula take place nearly seamlessly. Such cooperation and communication occur between networks at nearly every level from national, regional, and continental, to across the globe. The important next step is now to routinely include in this dialogue other scientific communities that could catalyze microscopy utilization. Efforts by Latin America Bioimaging (LABI)[18] to engage with regional structural biology community (CEBEM) and medical imaging community (SIPAIM) demonstrates an important early success. Especially important are those that represent research fields with key microscopy users, including but not limited to cell biology, developmental biology, infectious disease, cancer biology, histopathology, and neuroscience. Additionally, there are also major international biomedical research networks, such as the Institut Pasteur, that should be key allies for translating microscopy adoption to scientific output. Forging such international strategic partnerships with the global imaging community need to be prioritized and secured to leverage this missed potential. Forming scientifically integrated networks will constitute a virtuous cycle toward promoting microscopy uptake that will lead to expedited scientific output.

Role of tool developers to validate their inventions

Microscopy centers with state-of-the-art instruments and technical expertise must serve as the centerpiece to anchor such integrated, collaborative partnerships[1]. In fact, it is especially crucial that such shared infrastructure is available in resource-limited regions[19]. However, such flagship platforms must be complemented by a more distributed approach. The cadre of do-it-yourself, frugal microscopes can fill this adoption gap to push uptake throughout these communities.

One of the advantages of frugal microscopes is their ease of customization for local needs. Their relatively small cost further lowers the entry barrier for resource-limited users. However, frugality has often supplanted performance as the highest priority for low-cost microscope design. This misplaced priority can create fertile ground for technologies that over-promise and under-deliver, especially when teaching microscopes are touted as research instruments[20]. Ill-advised adoption of these inappropriately promoted instruments can do more harm hampering scientific output for several reasons. Firstly, scientists who are already resource-constrained may have only one opportunity to acquire a single microscope. A microscope that fails to support rigorous and quantitative science not only squanders limited resources, but it also handicaps the very scientist who needs it the most and who can weather scientific setbacks the least. Secondly, such under-delivery further fuels the incorrect belief that microscopy is not a worthwhile technique and/or is a high-end tool reserved for affluent regions. However, the most devastating outcome of relying on low performance, frugal microscopes is when the significant flaws in data quality fail to withstand the scrutiny of peer review. This can further perpetuate the already pervasive and biased perception in the Global North that resource-constrained communities can only produce sub-par science.

On the contrary, developers of most advanced microscopes not only delineate what their instruments are best suited to address, they are also careful to document their limitations[21–25]. This unwavering sense of accountability should be equally, if not more, important when developing low-cost microscopes to foster the necessary trust in this nascent technology. However, thorough validation involves more than just technical characterization. The instrument must be vetted for the applications and the environments in which it will be deployed. The Squid[26], Octopi[5], LoaScope[27,28], and openFrame[29] systems provide exemplar case studies in this regard. These efforts did not merely provide an inexpensive microscope design but have been coupled with targeted and persistent campaigns to pair their unique capabilities with local scientific needs. Additionally, these initiatives not only served to validate their instruments, e.g. the effort by Bharadwaj et al.[30], but also helped shape the very environment and the well-matched applications that sustain their long-term adoption. It is important to also point out that many researchers with limited resources view open-source tools as too technically demanding to adopt, preferring to rely on commercially supported systems. This is indeed an untapped market for manufacturers, such as Thorlabs, Inc., who have successfully lowered their manufacturing costs for routine research-grade microscopes. Likewise, open-source microscopes that have transitioned to commercial production, such as openScope and Cephla (based on the openFrame and Squid designs, respectively) have witnessed further increases in adoption. However, dissemination and commercialization, while necessary, are tedious and time-consuming. They require stamina and strategic acumen that most tool developers may not have the luxury to commit. Without the explicit vision and support of initial stakeholders who fund such technology development, newly developed tools can languish in oblivion rather than empower their target users. Such outcomes are ultimately self-defeating for both developers, funders and researchers alike.

Role of funders to incentivize sustained microscopy utilization

It is especially encouraging that many funders are increasingly aware and supporting of the power of open-source tools that can be easily deployed. But the effectiveness of a technology is ultimately measured by its uptake. Funders who also support a comprehensive strategy for validating, disseminating and adopting new technologies in their portfolios will maximize the return on their investment. To expect an already resource-constrained scientist to blindly accept the transformative power of microscopy severely underestimates the risk and investment inherent in such an undertaking. This barrier calls for careful derisking, which must include (i) well validated and curated instruments, (ii) committed image analysis support, (iii) availability of imaging-related reagents tailored for the technology, and (iv) trained technical personnel. Together, these factors should exist within a multidisciplinary culture where local physical scientists and engineers work with biologists to develop and apply local imaging capabilities. Devoid of such a holistic ecosystem, a nascent technology is left to fend for itself. This so-called "attrition" approach will prematurely cripple disruptively enabling technologies.

Leveraging frugal microscopy is only part of a broader strategy for increasing utilization of imaging technologies. Access to more advanced microscopy techniques must complement these efforts to fully empower researchers. However, advanced imaging instrumentation can be cost-prohibitive even in relatively affluent environments and service contracts are typically unaffordable, if they are even available, in most LMICs. Early recognition of the value of capacity sharing was demonstrated with the formation of various open-access platforms such as the Advanced Imaging Center at Janelia[14,31], Euro-BioImaging[32], and the EMBL Imaging Centre[33]. This strategy has started to gain footing in more resource-constrained environments with the advent of other platforms in the Global South, such as the Africa Microscopy Initiative (AMI)[3], and the Advanced Bioimaging Unit (UBA)[34] in Latin America, among others. While these continental-focused, centralized platforms are predominantly supported by international funders, national and local governments must recognize the need and shoulder some responsibility for funding regional core facilities to provide a continuum of access to imaging technologies to researchers at every stratum[19]. A stellar example of this is BioRTC[35] – supported by the Yobe State government in Nigeria – which is now a key training and access hub for the West African community. This local access to robust, research-grade foundational imaging technology is essential to allow scientists to explore imaging in their own settings, and to develop their work to a level best able to leverage the advanced instruments available in continental hubs.

Discussion

The impact of global efforts in microscopy technology dissemination will be indelible. Together, these programs and initiatives have created a solid foundation for training, accessibility, infrastructure, and networking that will empower underserved scientific communities for years to come. In fact, the community has evolved from individual initiatives to a global movement, reaching a point of maturation. The focal point of this paper is therefore not whether these platforms should be built in the first place, but rather how to ensure biologists take advantage of them. The global microscopy community has united in recognition of the need to set our sights on crossing the finish line of technology uptake – ensuring that microscopy technologies will be widely adopted to generate scientific output.

Certainly, travel restrictions, prohibitive and discouraging technology importation taxes, difficulty in sample shipment, as well as faltering scientific funding support all constitute political headwinds to hamper technology uptake. However, it remains important, albeit dispiriting at times, to examine how global programs have fallen short in creating demand for microscopy in underserved regions. In fact, the need has not kept pace with both technology development and the fervor around dissemination efforts. This lack of headway permeates the entire microscopy adoption landscape, from early exploration of imaging techniques to the sustained utilization of the technology. Despite its unique ability to span large biological length scales and its versatility in driving both quantitative and exploratory science[17], modern quantitative microscopy remains largely a novelty unfamiliar to scientists in resource-limited regions[17]. Historically, this is a chasm caused by the prohibitive cost of most commercial microscopes. The concept of using a microscope to tackle an experimental question has rarely seemed feasible to many scientists. Their preconceived notion that microscopy is a costly technique has hardly been dispelled by the increasing availability of low-cost microscopes for three key reasons: (i) the lagging appreciation of the power of modern, quantitative microscopy, (ii) the lack of awareness of affordable microscopy solutions, and (iii) the lack of documented performance verification and limitations for many low-cost, bespoke microscopes. Until these issues are resolved, this hesitancy will persist to the detriment of researchers themselves.

We emphasize that these issues must be tackled in parallel. First, microscopy workshops must be tailored to local needs, including customizing the curriculum for the local research interests, emphasizing instrumentation available to the attendees' communities, and highlighting local successful pilot studies if available. Microscopy communities must reach out to their regional scientific societies and cogently articulate how various modern imaging techniques that are accessible to them can tackle unanswered questions. Second, it is essential that low-cost microscopes are appropriately curated, validated, and de-risked so that their respective capabilities can be better matched to the experimental needs of under-privileged scientists. This will minimize the over-promises commonly seen whereby educational microscopes are being promoted as research grade instruments. Failure to do so can lead to confusion and entrenched disaffection toward microscopy among end-users. Third, the global imaging community must establish standards against which the performances of low-cost, research-grade microscopes can be evaluated and verified. This will allow various systems to be compared on a level playing field, facilitating informed choice by end users.

While these measures go a long way in persuading life science communities of the power of microscopy, long-term technology adoption and subsequent scientific output demand significantly more than just increased awareness. Successfully convincing a researcher to try a new technology does not automatically translate into enduring adoption. An effective strategy not only needs to include long-term accessibility, but also the necessary continued ancillary support. In the case of light microscopy, this includes easy access to local microscopy expertise, image analysis and imaging reagents, as well as the ability to maintain, adapt and upgrade instruments[1,18]. The importance of including these components as part of any capacity-building effort cannot be overstated.

Last but not least, funding organizations should not mistake the promise of tool sharing for widespread adoption. Technology dissemination relies on teams who know how to formulate effective strategies and implement them. Tool developers may not necessarily be the best dissemination experts (and vice versa). Their creativity and energy can oftentimes be better spent on technology development[14], while tasking dissemination and training to microscopy networks and imaging scientists working in core facilities. More importantly, dissemination requires significant, committed investment. While many international funders are keen on seeding initial funds to kick start dissemination efforts, long-term sustainability must also be the responsibility of local and regional funders – who require a clear return on their investment. Supporting their national scientists to explore unfamiliar tools and their long-term utilization can directly enable scientific output. Funders would soon recognize that their investments increase the scientific competitiveness of their country, which will translate to an increase of brain-gain, better health research and in the long-term underpin the prosperity and well-being of their people.

The road to technology uptake is paved on the foundation of dissemination efforts. To that end, the global imaging community has done an exceptional job not only in building the necessary groundwork but in setting an excellent example of how communities with disparate resources can come together with a unified sense of purpose. The rapid alignment of missions from imaging networks, tool builders, and funders is a testament to that shared vision. It firmly positions the community on the cusp of success. If there ever was a question of whether lagging technology adoption rates had been the result of a misstep, the answer would be a resounding no. In fact, without technology dissemination, we cannot even begin to explore its adoption. However, looking back at our approach thus far, there is indeed a missing next step. The global imaging community has not yet set technology uptake to facilitate scientific output as the final goal. If we continue to ignore this blind spot, this missed step can spiral into an unfortunate missed opportunity. However, the imaging networks are robust and integral. With careful retooling of our approach and messaging, we have the necessary platforms and collective resolve to rapidly pivot and meet the only success metric that matters – scientific output.

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