

Retinopathy of prematurity care in Colombia: workforce distribution, geographic accessibility, and emerging practice patterns

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Article

Keywords: geographic accessibility, health policy, referral systems, retinopathy of prematurity, teleophthalmology, workforce distribution

Posted Date: September 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10819022/v1>

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Additional Declarations: No competing interests reported.

Abstract

Background

Retinopathy of prematurity (ROP) is a leading cause of preventable childhood blindness, and timely screening and treatment are essential for preserving vision. Because ROP care depends on repeated surveillance, referral coordination, and access to specialized ophthalmic services, geographic and workforce constraints may substantially influence outcomes. However, the national organization, accessibility, and service capacity of ROP care in Colombia have not been systematically evaluated. This study assessed the distribution, scope of services, accessibility, and emerging practice patterns within Colombia's ROP care system.

Methods

This cross-sectional geospatial health services study linked a clinically validated national registry of pediatric ophthalmologists and retina specialists providing ROP care with population and travel-time datasets. Provider characteristics, service capabilities, delivery models, and population-weighted accessibility to screening and treatment services were evaluated using a nationwide least-cost path model.

Results

As of September 2025, 54 ROP providers were identified, including 29 pediatric ophthalmologists (53.70%) and 25 retina specialists (46.30%), who are practicing across 51 of Colombia's 1,103 municipalities (4.62%). Provider distribution was highly urban, with 93.10% of pediatric ophthalmologists and 100.00% of retina specialists located in urban municipalities. Most providers offered both screening and treatment services (82.76% of the pediatric ophthalmologists and 80.00% of the retina specialists). Laser photocoagulation and intravitreal anti-vascular endothelial growth factor therapy were available through 87.04% and 81.48% of providers, respectively, whereas 25.93% reported capability in vitrectomy, all of whom were retina specialists. Telemedicine or hybrid care models were used by 22.22% of the providers. Accessibility analyses revealed substantial screening inequities: 41.60% of the population lived more than 120 minutes from pediatric ophthalmologists, and 46.30% lived more than 120 minutes from retina specialists. Seven providers (12.96%) reported routinely using topical ketorolac or nepafenac off-label for early-stage disease.

Conclusions

Colombia's ROP care system relies on a small, urban-concentrated workforce and faces substantial barriers to screening accessibility. The emergence of off-label prophylactic practices warrants

prospective clinical and economic evaluation.

1. Introduction

Retinopathy of prematurity (ROP) is a vasoproliferative retinal disorder of preterm infants and remains a leading cause of preventable childhood blindness worldwide. Visual outcomes depend on timely identification of at-risk infants, reliable surveillance, and prompt treatment of referral-warranted disease. When delivered within recommended therapeutic windows, laser photocoagulation and intravitreal anti-vascular endothelial growth factor (anti-VEGF) therapy substantially reduce the risk of retinal detachment and irreversible vision loss. However, because disease progression may occur rapidly, delays in screening, loss to follow-up, and barriers to treatment continue to compromise outcomes despite the availability of effective interventions [1–4].

Unlike many ophthalmic conditions, ROP is managed through a longitudinal care pathway spanning multiple clinical settings and requiring coordination among neonatologists, ophthalmologists, caregivers, and referral institutions. Screening begins during neonatal hospitalization, often continues after discharge, and relies on repeated examinations within a narrow developmental window [5–7]. Treatment delivery further requires specialized personnel, access to laser infrastructure or anti-VEGF therapy medication (typically bevacizumab and ranibizumab), neonatal anesthesia support, and referral systems capable of facilitating timely intervention. Advanced surgical management is generally restricted to tertiary referral centers [1, 8–10].

As a result, the effectiveness of ROP care depends not only on treatment availability but also on the accessibility and organization of the services that support screening, referral, treatment, and posttreatment surveillance [1, 2, 11–14]. Access barriers can disrupt this continuum by increasing travel demand across repeated visits while interacting with transportation limitations, caregiver availability, and healthcare system fragmentation. Consequently, access to screening services may be a critical determinant of whether infants enter the care pathway early enough to benefit from available therapies [8, 15–18].

These challenges are particularly relevant in low- and middle-income countries, where the proportional expansion of specialized ophthalmic capacity has not always kept pace with improvements in neonatal survival. Service concentration within major metropolitan centers may therefore create substantial geographic inequities for infants residing in peripheral and underserved regions [1, 2, 7, 10, 19, 20]. Despite recognition of these challenges, most evaluations rely on provider-to-population ratios or straight-line distances that inadequately capture real-world travel constraints and rarely distinguish accessibility to screening from accessibility to treatment.

In Colombia, a country characterized by considerable geographic, infrastructural, and healthcare-system heterogeneity, the national organization of ROP services has not been systematically evaluated using travel-time-based accessibility metrics. This evidence gap limits workforce planning, the identification

of underserved populations, the prioritization of service expansion, and the strategic implementation of teleophthalmology programs.

Accordingly, this study presents a nationwide geospatial and service-delivery assessment of ROP care in Colombia. The objectives were to (1) characterize the composition, geographic distribution, service scope, and delivery modalities of the national ROP workforce; (2) estimate population-weighted accessibility to screening and treatment services using modeled travel-time thresholds; and (3) identify emerging clinical practices arising in response to contemporary challenges in ROP care delivery. Collectively, these findings are intended to inform health-system planning and provide a foundation for future investigations evaluating the relationships among accessibility, healthcare utilization, and clinical outcomes.

2. Methods

2.1. Study design and scope

This national cross-sectional geospatial health-services study characterized the distribution, service capacity, and population-weighted geographic accessibility of specialized ophthalmic care for ROP in Colombia. The prespecified analytic workforce comprised pediatric ophthalmologists and retina specialists who were verified as actively providing ROP screening, treatment, or both.

These two subspecialties were selected because the geospatial analysis was designed to quantify access to the specialized ophthalmic service nodes at which retinal examination, ROP classification, and/or definitive ocular treatment are delivered. Neonatologists and other neonatal-care professionals are integral to ROP prevention and care through identification of at-risk infants, coordination of screening, clinical management, referral, and longitudinal follow-up; however, access to neonatal services was outside the scope of the present analysis and these professionals were therefore not included in the ophthalmic provider denominator [2, 21, 22].

General ophthalmologists were not enumerated as a separate workforce category because the study was designed a priori to characterize the subspecialist network providing ROP services. Within this analytic framework, general ophthalmology was considered part of the broader referral environment rather than a separate target workforce. This restriction defines the scope of the study and should not be interpreted as implying that subspecialty designation alone determines competence in ROP care; appropriately trained ophthalmologists may participate in ROP screening according to local practice and credentialing arrangements.

2.2. Ethical considerations

All methods were carried out in accordance with relevant institutional guidelines and applicable regulations.

The study protocol was reviewed by the microscopIA Institutional Review Board, an internal institutional research-oversight body, which determined that the investigation did not constitute research involving human participants. The study used population-level and professional service-delivery information and did not involve patients, patient-level clinical data, identifiable human-subject information, human biological materials, experimental interventions, or enrollment of individuals as research participants. Provider contacts, as described below, were limited to verifying registry and service information and did not constitute recruitment or participation in human-subjects research.

No experimental protocols involving human participants or human biological materials were conducted. Accordingly, formal ethics approval for human-participant research and informed consent from research participants or their legal guardians were not applicable.

2.3. Provider and service-site identification and validation

Because Colombia does not maintain a centralized national registry of clinicians providing ROP care, a de novo national provider–service-site registry was constructed by triangulating multiple information sources. Candidate providers and practice sites were identified from national ophthalmology society rosters, postgraduate training records, institutional directories, publicly available professional databases, and regional referral networks.

Registry entries were validated independently within each ophthalmic subspecialty using a standardized service-verification protocol. Verification established active ROP service provision and the characteristics required for the health-services and geospatial analyses, including primary practice location, screening and treatment availability, procedural capabilities, care-delivery modalities, and selected ROP practice characteristics. Direct provider contact was used solely to confirm professional and service information required for registry validation; no patient-level information was collected through this process. When direct confirmation was unavailable or additional verification was required, institutional information was used.

Validation of the retina specialist registry was led by Dr. Marudys Stella Mestra Burgos, a retina specialist, study co-investigator, and coauthor with more than a decade of experience managing ROP, including care in rural and underserved settings in the Córdoba and Antioquia regions, and affiliated with the Colombian Association of Retina and Vitreous (*Asociación Colombiana de Retina y Vítreo*). Validation of the pediatric ophthalmologist registry was led by Dr. Claudia Zuluaga Botero, president of the Pan-American Society of Retinopathy of Prematurity 2025–2027 (*Sociedad Panamericana de Retinopatía del Prematuro*).

Discrepant or uncertain registry entries underwent repeated source verification and clinical adjudication until consensus was reached. Provider identity was retained only as required for registry construction, verification, and deduplication, and was removed before geospatial modeling. Workforce and service characteristics were summarized in aggregate at the provider level, whereas geographic accessibility analyses were conducted at the service-site level. No provider identities were disclosed in study outputs.

2.4. Geolocation of facilities

A two-stage geolocation protocol was used to identify active ROP service sites and assign geographic coordinates for spatial analysis. First, trained abstractors used Google Maps (Google LLC, Mountain View, CA, USA) to determine the coordinates of each provider's primary ROP practice location. For specialists practicing across multiple facilities, the site where ROP care was most routinely delivered was selected.

Second, all coordinates underwent independent quality assurance—senior reviewers cross-validated facility locations against national health registries, institutional accreditation records, and high-resolution satellite imagery. Discrepant or uncertain locations were subjected to repeated verification until consensus was achieved. Facilities lacking reliable geolocation data or confirmation of active ROP service delivery were excluded from the analysis.

Based on published evaluations of Google Maps–based geocoding in comparable settings, the positional accuracy was estimated to be within approximately 250 meters [23–26]. This level of precision is sufficient for integration into national-scale travel-time accessibility models and population-based catchment analyses.

2.5. Population distribution data

The population distribution was modeled using a composite gridded population surface designed to represent demographic variation across Colombia's urban, peri-urban, rural, and geographically isolated regions.

The primary population source was the National Administrative Department of Statistics (*Departamento Administrativo Nacional de Estadística* [DANE]), which provides 100-meter–resolution population estimates derived from the 2018 national census and updated using 2025 demographic projections. These census-based layers served as the reference population dataset throughout the analysis.

To improve representation in sparsely populated and geographically complex regions—including the Amazon, Orinoquía, Pacific, and rural Andean territories—two supplementary datasets were incorporated: the Kontur Global Population Dataset (Kontur Inc., Tallinn, Estonia) and the Global High Resolution Population Density Maps (Meta Platforms, Inc., Menlo Park, CA, USA). These datasets were used exclusively to refine population allocation in locations where census-based mapping may underrepresent dispersed settlements.

Dataset integration followed a deterministic harmonization framework. Official DANE values were retained in all cells containing nonzero population counts. Cells classified as unpopulated by the DANE but exhibiting evidence of settlement in the ancillary datasets received provisional population allocations based on a settlement-weight index derived from the combined Meta and Kontur layers, with Meta values prioritized when both sources were available. These allocations were subsequently rescaled

within each municipality to preserve official DANE population projections. Cells with zero population across all datasets remained unchanged.

All population layers were reprojected to Colombia's official coordinate reference system, MAGNA-SIRGAS EPSG:4686 (Instituto Geográfico Agustín Codazzi, Bogotá, Colombia), harmonized to a common 100-meter grid using nearest-neighbor resampling, and aligned with official municipal and departmental boundaries. Municipal, departmental, and national totals were reaggregated following harmonization to verify consistency with official population projections. The resulting composite population surface served as the basis for all accessibility and population-catchment analyses.

2.6. Road network assembly and friction-surface development

Accessibility modeling assumed that motorized ground transportation was the principal referral pathway for ROP screening and treatment in Colombia. Consequently, analyses were restricted to the national road network and did not incorporate aeromedical or fluvial transport.

Road network data were obtained from OpenStreetMap (OpenStreetMap Foundation, London, UK) using the HCMGIS plugin within QGIS 3.16 (QGIS Development Team, Open Source Geospatial Foundation, Beaverton, OR, USA). Administrative boundaries were obtained from the GADM v3.6 database (University of California, Santa Barbara, CA, USA).

Road segments were classified into five functional categories—trunk, primary, secondary, tertiary, and residential—according to OpenStreetMap tagging conventions. Maximum travel speeds ranging from 10 to 80 km/h were assigned using Colombian transportation regulations (Law 1239 of 2008) and published estimates reflecting emergency and public-transport operating conditions [27].

The cleaned road network was rasterized to generate a continuous speed surface. Cells intersecting mapped road segments were assigned category-specific travel speeds. To preserve connectivity for populated cells that did not directly intersect a mapped road segment, off-road cells were assigned a background speed of 5 km/h, allowing linkage to the nearest traversable road cell. Long-distance movement remained constrained to the motorized road network.

A friction surface was subsequently generated by converting travel speeds to time costs, expressed in seconds per meter. This layer provided the foundation for all the accessibility analyses.

2.7. Travel-time modeling

Accessibility was estimated using least-cost path analysis implemented through the *r.cost* module of GRASS GIS 7.8 (Open Source Geospatial Foundation, Beaverton, OR, USA) within QGIS 3.16. The algorithm identifies the lowest-cost route across the friction surface and calculates the cumulative travel time from each populated grid cell to the nearest eligible service site.

Separate national accessibility surfaces were generated for facilities staffed by ROP-trained pediatric ophthalmologists and retina specialists. Each verified provider location was encoded as a destination node, and the minimum travel time was calculated across the national territory.

Two care-delivery scenarios were evaluated—the first assessed access to outpatient screening services, which require repeated examinations throughout a prolonged surveillance period. Accessibility was categorized into five operational intervals: ≤ 30 , 31–60, 61–90, 91–120, and > 120 minutes. These thresholds were selected as proxies for assessing the potential for timely initiation of screening and the feasibility of follow-up continuity.

The second assessed access to definitive treatment following identification of treatment-requiring disease. Treatment-capable facilities were defined as sites reporting laser photocoagulation and/or intravitreal anti-VEGF therapy. Accessibility was categorized into clinically relevant intervals of ≤ 48 hours, 49–72 hours, and > 72 hours, consistent with recommended treatment windows following diagnostic confirmation [1, 2].

Areas lacking mapped road connectivity were classified as nonreachable under the ground-transport assumption and analyzed separately. These territories were excluded from the accessibility categories to avoid misclassification across scenarios with differing levels of clinical urgency.

2.8. Population–time accessibility overlays

Population coverage within each accessibility interval was estimated by overlaying national accessibility surfaces onto the harmonized population grid. Population counts were aggregated using zonal statistics to generate population-weighted accessibility estimates for Colombia's 32 departments and 1,103 municipalities [28].

Descriptive statistics and graphical outputs (including histograms and kernel density plots) were generated in Python 3.10 (Python Software Foundation, Wilmington, DE, USA) using NumPy (v1.25), Matplotlib (v3.8), and Seaborn (v0.13) to characterize the national distribution of travel times and to visualize geographic disparities and right-skewed accessibility patterns.

3. Results

3.1. National workforce composition and service scope

As of September 2025, 54 ophthalmic subspecialists were geolocated and verified as actively providing ROP services in Colombia: 29 pediatric ophthalmologists (53.70%) and 25 retina specialists (46.30%). Most providers delivered both screening and treatment at their primary practice site, including 24 pediatric ophthalmologists (82.76%) and 20 retina specialists (80.00%). Screening-only services were reported by 3 pediatric ophthalmologists (10.34%) and 2 retina specialists (8.00%), whereas treatment without in-house screening was reported by 2 pediatric ophthalmologists (6.90%) and 3 retina specialists (12.00%), typically through referral-based workflows.

Procedural capacity was concentrated around laser photocoagulation and intravitreal anti-VEGF therapy, reported by 47 (87.04%) and 44 (81.48%) providers, respectively. Advanced surgical capability was less common: 14 retina specialists (25.93% of all providers) reported pars plana vitrectomy capacity, whereas no pediatric ophthalmologists reported vitrectomy involvement.

Twelve providers (22.22%) reported using telemedicine-enabled delivery models. Five (9.26%) operated exclusively through telemedicine, and seven (12.96%) used hybrid workflows that combined onsite evaluations with remote follow-up or interfacility consultation via digital widefield retinal imaging. The remaining 42 providers (77.78%) delivered exclusively in-person services.

3.2. Geographic distribution of providers and urban–rural placement

ROP-trained providers were distributed across 51 municipalities, representing 4.62% of Colombia's 1,103 municipalities [28]. Pediatric ophthalmologists were present in 36 municipalities (3.26%), retina specialists in 29 (2.63%), and both subspecialties in 14 (1.27%).

Provider placement was predominantly urban. Overall, 27 pediatric ophthalmologists (93.10%) and all retina specialists (100.00%) were located in urban municipalities; only 2 pediatric ophthalmologists (6.90%) practiced in rural municipalities.

3.3. Accessibility to screening services

Population-weighted travel-time modeling demonstrated substantial geographic variation in potential access to ROP screening. With respect to pediatric ophthalmologist–led screening (Fig. 1), 25.60% of the national population resided within 30 minutes of a provider, 17.20% within 31–60 minutes, 9.60% within 61–90 minutes, 3.10% within 91–120 minutes, and 41.60% more than 120 minutes away.

Access to retina specialist–led screening was more limited (Fig. 2). Approximately 18.40% of the population resided within 30 minutes, 13.20% within 31–60 minutes, 11.50% within 61–90 minutes, 7.70% within 91–120 minutes, and 46.30% more than 120 minutes away.

3.4. Accessibility to treatment services

Modeled access to definitive ROP treatment was broader than access to screening (Figs. 3–4). An estimated 97.00% of the national population resided within 48 hours of a treatment-capable provider, defined as a pediatric ophthalmologist or retina specialist who reports performing laser photocoagulation and/or intravitreal anti-VEGF therapy. Approximately 0.01% of the population had modeled travel times of 49–72 hours.

3.5. Subnational heterogeneity and unreachable areas

The travel-time distributions were right-skewed, with long tails reflecting prolonged travel times for populations outside major urban corridors (Figs. 1–4). High-access clusters were concentrated in Bogotá D.C., Medellín, and Cali, where subspecialty density and neonatal referral infrastructure are most developed. In contrast, substantial portions of the Pacific, Orinoquía, and Amazon macroregions fell within the longest screening travel-time category (> 120 minutes) or were classified as unreachable within the modeled ground-transport network. Overall, 2.99% of the population resided in areas classified as unreachable for both screening and treatment.

3.6. Emerging off-label practices

Seven providers (12.96%) reported using off-label, nonstandard management strategies for infants with early-stage ROP, including prophylactic topical nonsteroidal anti-inflammatory drugs (NSAIDs), particularly ketorolac and nepafenac.

The biological rationale underlying this practice was the hypothesis that modulating inflammatory pathways involved in retinal neovascularization could reduce the risk of disease progression during the surveillance period preceding treatment-requiring ROP. Clinicians further noted that ketorolac does not penetrate the cerebrospinal fluid and that both ketorolac and nepafenac have generally demonstrated favorable tolerability profiles in the ophthalmic literature [29–37].

During provider verification, clinicians identified delayed screening, interrupted surveillance, and nonadherence to follow-up among high-risk infants as the principal factors motivating the adoption of these approaches. Providers also cited the low acquisition cost, broad availability, and perceived safety of topical NSAIDs as favorable implementation characteristics. Both agents were reported to be covered by the subsidized and contributory health insurance regimes and typically cost approximately USD 5–26 per unit at full retail price.

These practices represented an emerging pattern of care not currently incorporated into international ROP management guidelines. Neither ketorolac nor nepafenac ophthalmic formulations are approved for neonatal administration; therefore, their use in this context was entirely off-label. Clinicians additionally reported that adoption occurred through informal mentoring relationships and specialist referral networks, resulting in broadly similar implementation approaches across participating providers.

4. Discussion

4.1. Accessibility, screening, and pathway performance

This national delivery and geospatial assessment provides insight into how the organization of ROP services in Colombia may influence timely entry into care. These findings support a central interpretation: effective ROP management depends not only on the availability of proven therapies but also on the reliability of the screening, referral, treatment, and follow-up pathway through which infants

access those therapies. In this context, modeled accessibility should be interpreted as a measure of spatial feasibility rather than a direct measure of health-system performance.

An important distinction exists between potential accessibility and realized access. Network-modeled travel times estimate the shortest feasible route under the assumptions of the transport model but do not capture referral activation, appointment availability, insurance authorization processes, caregiver constraints, neonatal transport readiness, workforce availability, or facility-level capacity. Consequently, favorable geographic coverage should not be interpreted as evidence that infants routinely receive timely care. In ROP, where progression may occur rapidly once treatment-requiring disease develops, delays due to administrative, logistical, or organizational barriers may substantially affect outcomes despite the availability of geographically accessible services [1, 10].

The most important implication concerns screening accessibility. Unlike treatment, which is typically episodic, ROP surveillance requires repeated examinations across a narrow developmental window. Travel burden therefore accumulates over multiple visits and may contribute to missed appointments, delayed diagnosis, and progression before treatment-requiring disease is recognized. Screening accessibility should consequently be interpreted as a proxy for the feasibility of maintaining longitudinal adherence rather than a one-time access metric. These findings suggest that accessibility to screening services may represent a more important determinant of preventable vision loss than treatment availability alone.

Collectively, the results support the evaluation of ROP services as a care pathway rather than as isolated points of service delivery. Downstream treatment capacity cannot compensate for upstream diagnostic failure. Treatment capability is meaningful only when infants enter the pathway, remain engaged in follow-up, and are appropriately escalated as disease progresses.

4.2. Workforce organization and service delivery

The identification of 54 verified ROP-trained subspecialists serving a country of more than 53 million inhabitants highlights the challenges of achieving equitable coverage through workforce expansion alone [38]. Although increasing numbers of specialists remain important, the findings suggest that service organization, referral efficiency, and network design may be equally influential determinants of access and continuity of care.

The coexistence of screening-only, treatment-only, and referral-based care models indicates substantial heterogeneity in service delivery. In these arrangements, continuity of care depends heavily on the reliability of handoffs between providers and institutions. When screening and treatment are geographically separated, timely intervention becomes dependent on communication quality, documentation transfer, transportation coordination, referral efficiency, and the availability of urgent appointments. As care pathways become increasingly fragmented, the gap between spatial accessibility and effective access may widen considerably.

The broad availability of laser photocoagulation and intravitreal anti-VEGF therapy suggests a substantial national capacity to deliver first-line treatment despite the limited size of the specialist workforce. However, the relatively limited availability of advanced vitreoretinal surgery may represent an important downstream bottleneck for infants who present late or progress despite initial therapy. These findings underscore the need to interpret modeled treatment accessibility cautiously.

Treatment-capable facilities were defined as those with the availability of laser photocoagulation and/or anti-VEGF therapy. In contrast, accessibility was evaluated using clinically recommended treatment windows extending up to 72 hours after diagnosis. Consequently, comparably favorable treatment-accessibility estimates should be interpreted as representing the maximum acceptable interval for intervention rather than typical real-world access. In practice, delays arising from referral activation, transportation logistics, appointment scheduling, and facility readiness may substantially reduce effective accessibility despite apparent geographic coverage.

Collectively, these findings emphasize the importance of closed-loop referral systems, in which the completion of each step of the care pathway is actively verified. In ROP, reliable escalation from screening to treatment may be as important as geographic proximity itself in preventing avoidable vision loss.

4.3. Emerging clinical adaptations and off-label prophylaxis

One of the most notable findings was the identification of clinician-reported off-label prophylactic use of topical NSAIDs, particularly ketorolac and nepafenac, among a subset of providers managing infants with early-stage ROP. This emerging practice appears to have arisen in response to concerns regarding delayed screening, interrupted surveillance, and poor adherence to follow-up among infants residing in geographically or socioeconomically vulnerable settings.

Importantly, this observation should not be interpreted as evidence supporting effectiveness, safety, or guideline adoption. Rather, it may be viewed as a signal of system stress, reflecting clinicians' attempts to mitigate perceived risks associated with unreliable longitudinal follow-up. The emergence of such practices highlights how healthcare providers may adapt when the reliability of surveillance pathways is uncertain.

Nevertheless, the findings identify a potentially important research agenda. If early-stage pharmacologic prophylaxis is hypothesized to reduce progression during periods of limited follow-up reliability, this hypothesis warrants rigorous evaluation through multicenter randomized controlled trials. Future studies should assess not only efficacy and safety but also real-world effectiveness, implementation feasibility, adherence patterns, and interactions with referral and surveillance systems. Such investigations may help determine whether pharmacologic prophylaxis has a role within specific high-risk contexts or whether strengthening care delivery systems remains the more effective strategy.

4.4. Technology-enabled solutions: telemedicine, artificial intelligence, and imaging platforms

These findings suggest that improving ROP outcomes in geographically heterogeneous settings will require interventions that simultaneously address access, quality, and continuity of care. Technological innovations offer opportunities to extend specialist reach, improve screening efficiency, and strengthen pathway performance, but their impact depends on integration within coordinated systems of care.

Tele-ROP programs based on portable widefield retinal imaging and asynchronous image interpretation represent among the most immediately deployable strategies. Such systems can reduce travel requirements, improve access in underserved regions, and facilitate earlier identification of treatment-requiring diseases while allowing specialists to focus on interpretation and treatment rather than travel. However, successful implementation requires standardized image acquisition, trained personnel, quality assurance programs, secure image management, defined turnaround targets, escalation protocols, and sustainable reimbursement structures [1, 2, 39–42].

Artificial intelligence (AI)–assisted screening systems may improve efficiency by supporting image triage, prioritizing urgent cases, quality assessment, and diagnostic decision support. AI has the potential to reduce specialist workload and increase consistency across large screening networks, particularly in regions with limited subspecialty capacity. However, deployment should be approached cautiously. Clinical utility depends on robust external validation, calibration across diverse populations, governance frameworks, clearly defined escalation pathways, and medicolegal accountability. AI should therefore be viewed as a tool to augment specialist capacity rather than replace expert clinical judgment [1, 20, 43–46].

The integration of imaging devices, AI-assisted interpretation, telemedicine infrastructure, and digital coordination platforms may facilitate the development of learning health systems for ROP. Automated scheduling, longitudinal tracking, missed-visit alerts, referral monitoring, and national registries could improve retention and continuity of care while generating data for quality improvement. Because ROP outcomes depend as much on successful navigation through a complex care pathway as on diagnostic accuracy itself, digital coordination systems may ultimately prove as impactful as advances in imaging technology are [2, 47].

4.5. Policy implications and future directions

The findings support a shift in policy focus from nominal service coverage toward measurable pathway performance. In the short term, the highest-yield interventions are likely operational rather than technological. These include the standardization of eligibility and referral criteria, the scheduling of initial screening appointments before neonatal discharge, the implementation of closed-loop referral verification, and the development of regional escalation pathways with protected treatment capacity for urgent cases.

In the medium term, tele-ROP networks should be prioritized within underserved population clusters identified through geospatial analyses. Investment in portable imaging devices, technician training, contracted reading services, and performance monitoring may allow specialist expertise to be distributed more efficiently across geographically dispersed populations. Regional rotation models and shared-care arrangements may further extend specialist reach without requiring permanent workforce relocation.

In the longer term, ROP surveillance should be embedded within national neonatal health systems through the development of registries, standardized quality indicators, and routine geospatial reassessment. Metrics such as time to first screening, missed-visit rates, referral completion, time from diagnosis to treatment, and completion of posttreatment surveillance may provide more meaningful indicators of system performance than workforce counts alone.

4.6. Strengths and limitations

This study has several strengths. Provider locations and service characteristics were verified through structured clinical validation in the absence of a national registry, enabling a facility-level characterization of ROP service availability. The analysis distinguishes accessibility to screening and treatment services. It uses population-weighted travel-time modeling, which provides greater operational relevance than provider-to-population ratios or straight-line distance measures do. Reporting nonreachable territories separately also reduces the risk of misclassifying geographic isolation as merely prolonged travel time.

Several limitations should be considered. Population-weighted accessibility estimates do not directly represent neonatal risk distribution, and preterm birth incidence, neonatal intensive care unit catchment areas, and facility readiness metrics were not incorporated. The model assumes motorized ground transportation and does not account for fluvial or aeromedical transport pathways that may be relevant in selected regions. Most importantly, the analysis evaluates potential accessibility rather than observed healthcare utilization. Travel-time estimates were not linked to real-world screening completion, referral latency, treatment timing, or follow-up adherence. Future studies integrating geospatial accessibility data with neonatal clinical datasets, registry information, and health-system performance indicators will be essential for quantifying the relationship between geographic access and clinical outcomes.

5. Conclusions

This national assessment indicates that geographic burden, a limited subspecialist workforce, and a heterogeneous service organization may constrain the reliability of ROP screening and longitudinal follow-up in Colombia. These findings suggest that preventing avoidable ROP-related visual impairment depends not only on the availability of effective therapies but also on the performance of the care pathway that connects infants to those therapies. Future planning should therefore prioritize retention, timeliness, referral accountability, and coordinated service delivery while leveraging telemedicine, AI,

imaging technologies, and digital health infrastructure to transform spatial accessibility into effective access.

Abbreviations

AI

artificial intelligence

anti-VEGF

anti-vascular endothelial growth factor

DANE

Departamento Administrativo Nacional de Estadística (National Administrative Department of Statistics)

GADM

Database of Global Administrative Areas

GIS

Geographic Information System

HCMGIS

Ho Chi Minh City Geographic Information System plugin

NSAIDs

nonsteroidal anti-inflammatory drugs

QGIS

Quantum Geographic Information System

ROP

retinopathy of prematurity

VEGF

vascular endothelial growth factor.

Declarations

Funding: This study received no external funding from governmental agencies, commercial entities, or nonprofit organizations. The study was supported exclusively by institutional resources provided by microscopIA. The funder had no external role in study design, data analysis, interpretation, or preparation of the manuscript.

Competing interests: The authors declare no financial or non-financial competing interests relevant to this work.

Ethics approval: All methods were carried out in accordance with relevant institutional guidelines and applicable regulations. The study protocol was reviewed by the microscopIA Institutional Review Board, an internal institutional research-oversight body, which determined that the investigation did not constitute research involving human participants.

The study used population-level and professional service-delivery information and did not involve patients, patient-level clinical data, identifiable human-subject information, human biological materials, experimental interventions, or enrollment of individuals as research participants. Contacts with ophthalmic providers were limited to registry and facility verification, including confirmation of professional and service information required to construct and validate the ROP service registry; these contacts did not constitute recruitment or participation in human-subject research.

No experimental protocols involving human participants or human biological materials were conducted. Accordingly, formal ethics approval for human-participant research by an external research ethics committee was not required for this investigation.

microscopia's research group was formally recognized by the Colombian Ministry of Science, Technology and Innovation in Call 894 (2021).

Consent to participate: Not applicable. No individuals were enrolled as human research participants, and no patient or legal-guardian data were collected. Provider contacts were undertaken solely for registry and facility verification and did not constitute research participation. The senior clinical validators involved in registry development participated as study investigators and coauthors rather than as research subjects. Accordingly, informed consent from research participants or their legal guardians was not applicable.

Consent for publication: Not applicable. The manuscript contains no identifiable participant information, clinical images, or other personally identifiable human-subject material requiring consent for publication.

Availability of data, materials, and code: The population and geospatial datasets used in this study were derived from the sources described and cited in the Methods. The analytical datasets supporting the reported findings, including the de-identified provider–service-site registry and the analytic scripts used for the geospatial analyses, are available from the corresponding author upon reasonable request. Provider-identifying information used solely for registry verification and deduplication is not included in the analytical datasets made available for secondary use.

Author Contributions: JJRM led project execution, coordinated the geospatial analyses, generated the mapping outputs, and oversaw analytical quality control. JCL contributed to travel-time modeling, spatial analyses, and methodological refinement. DFEP, LSCB, SCP, and SAC contributed to registry development and curation, spatial-data verification, and consistency auditing. MSMB and CZB served as senior clinical investigators and led clinical validation of the retina-specialist and pediatric-ophthalmologist components of the national ROP registry, respectively. JR conceived the study, supervised its methodological development and execution, designed and oversaw the analytical strategy, contributed to quality assurance, secured institutional resources, interpreted the findings, and drafted the manuscript. JR serves as guarantor of the study. All other authors contributed to interpretation of the findings and critical revision of the manuscript. All authors reviewed and approved the final manuscript for submission.

Use of AI and digital writing tools: AI-assisted tools were used solely during manuscript preparation for language editing, clarity, and editorial refinement. ChatGPT (OpenAI, San Francisco, CA, USA), Rubriq (Research Square, Durham, NC, USA), and Grammarly (Grammarly, San Francisco, CA, USA) were used for these purposes. Turnitin (Turnitin LLC, Oakland, CA, USA) was used separately for similarity screening. These tools were not used for data collection, registry validation, geospatial or statistical analysis, interpretation of study findings, or generation of scientific conclusions. All AI-assisted output was reviewed and, where necessary, revised by the authors, who take full responsibility for the accuracy, integrity, and content of the manuscript.

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Figures

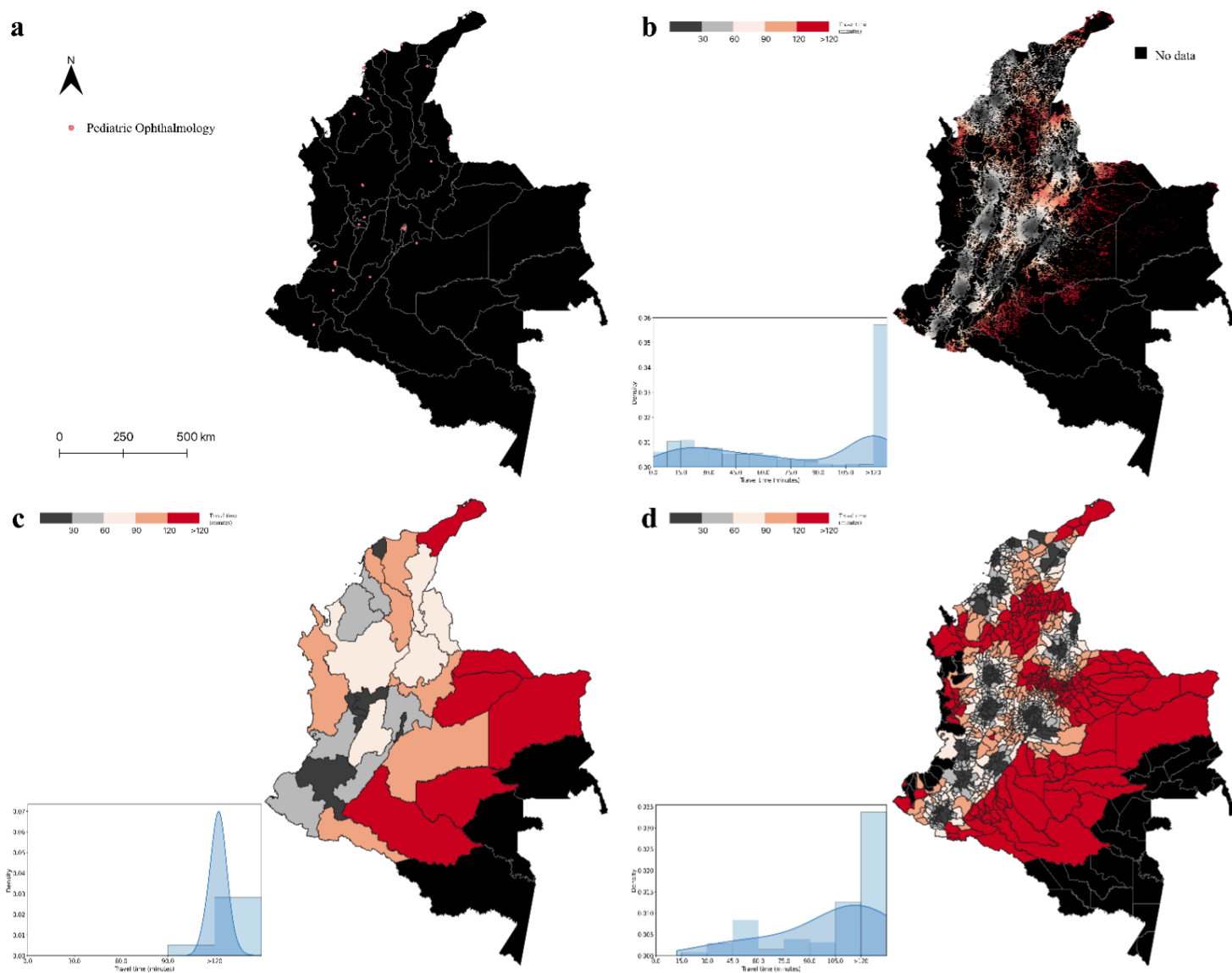


Figure 1

Travel-time accessibility to ROP screening by pediatric ophthalmologists in Colombia. Panel a shows the locations of verified pediatric ophthalmologists providing ROP screening. Panel b maps the modeled ground travel time to the nearest screening site. Panel c summarizes departmental population coverage by travel-time category. Panel d presents municipal-level coverage, highlighting within-department heterogeneity and screening “deserts.”

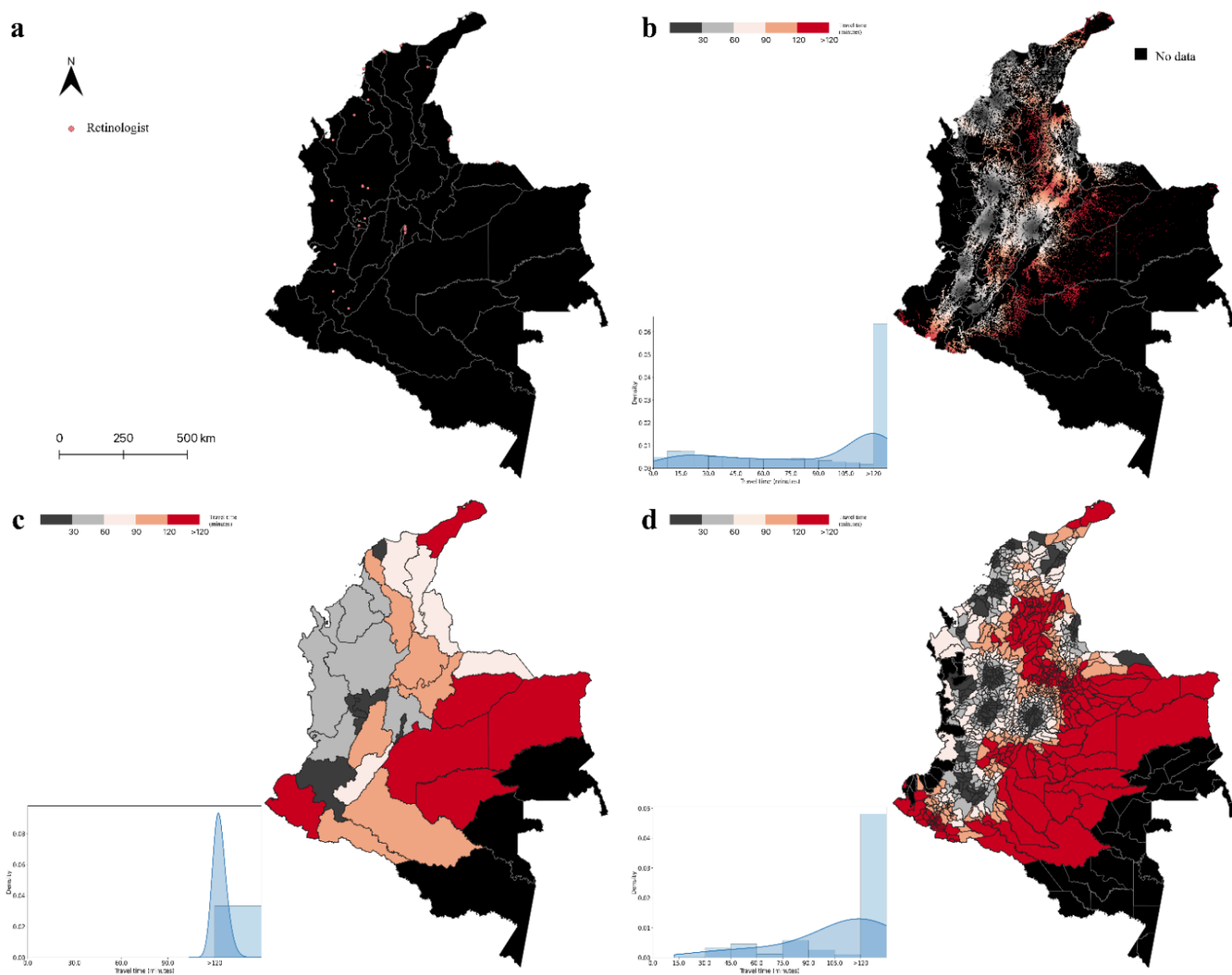


Figure 2

Travel-time accessibility to ROP screening by retina specialists in Colombia. Panel *a* shows the locations of the verified retinal specialists who provide ROP screening. Panel *b* maps the modeled ground travel time to the nearest screening site using the same screening thresholds as those in Fig. 1. Panel *c* summarizes departmental population coverage by travel-time category. Panel *d* presents municipal-level coverage, emphasizing subregional inequities and areas with limited screening reach.

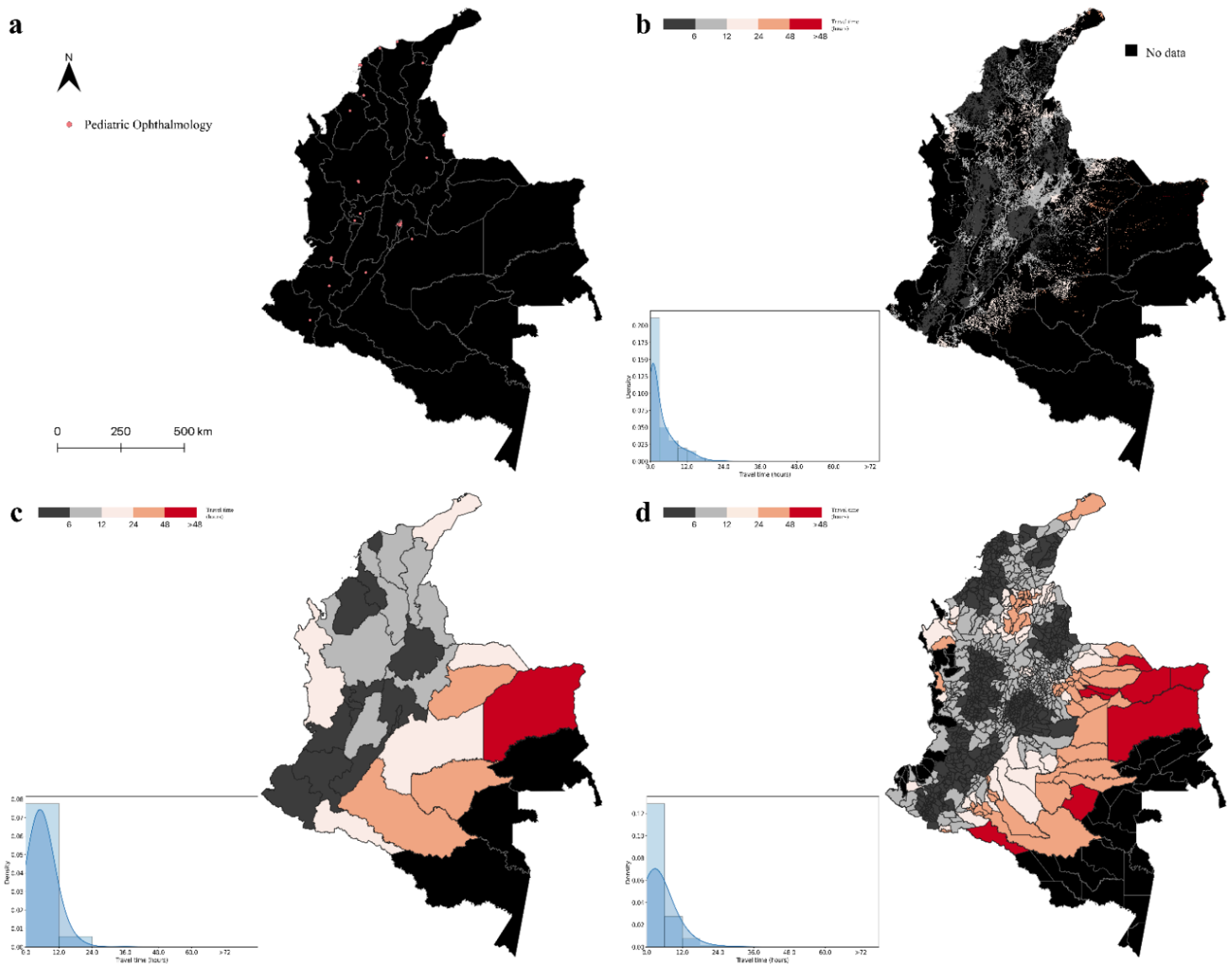


Figure 3

Travel-time accessibility to definitive ROP treatment by pediatric ophthalmologists in Colombia. Panel *a* shows the locations of pediatric ophthalmologists reporting the ability to provide definitive ROP treatment (laser photocoagulation and/or intravitreal anti-VEGF therapy). Panel *b* maps the modeled ground travel time to the nearest treatment-capable site, categorized as ≤ 48 hours, 49–72 hours, and >72 hours. Panel *c* summarizes departmental population coverage by category. Panel *d* presents municipal-level coverage, identifying areas with delayed or absent access to time-sensitive treatment.

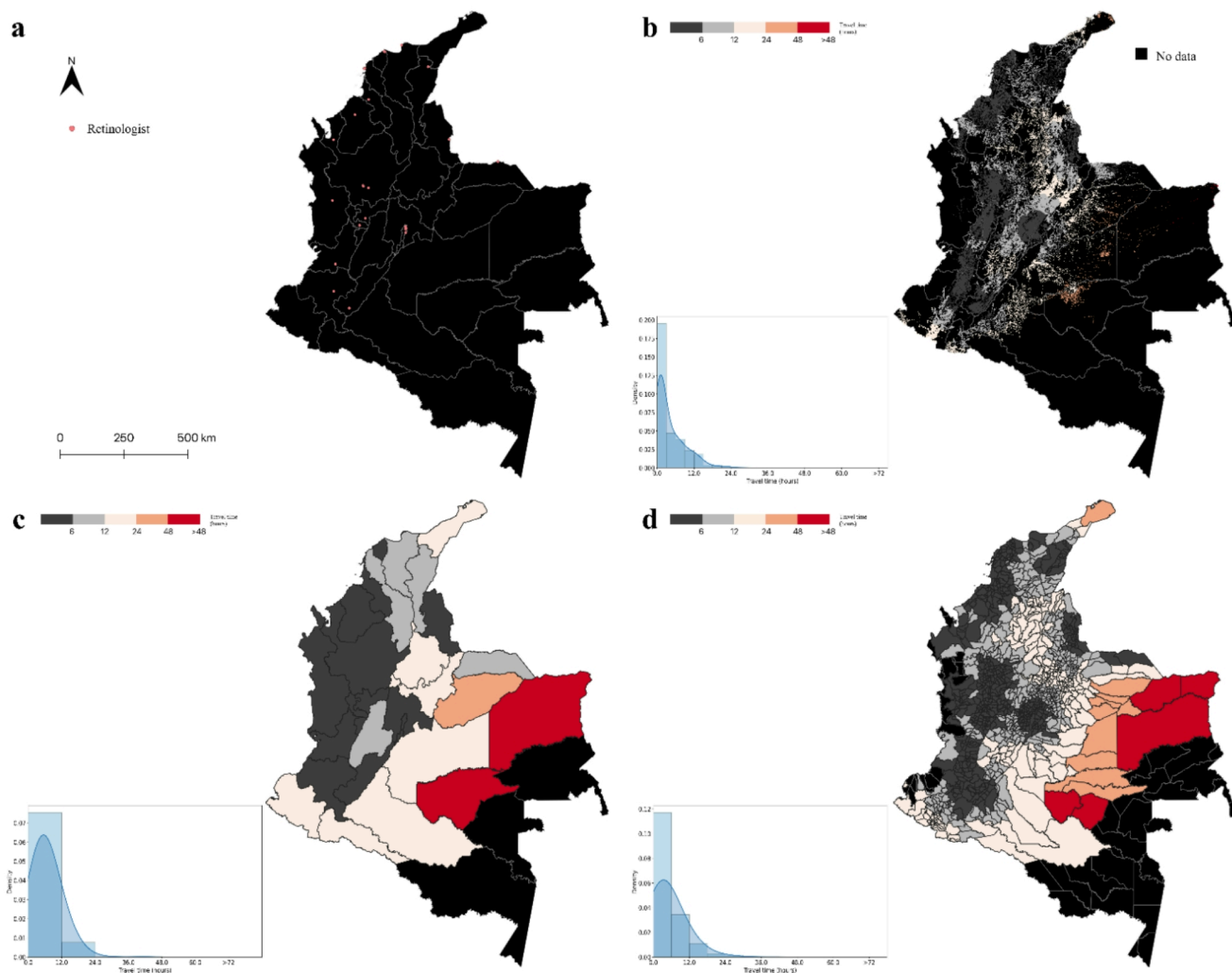


Figure 4

Travel-time accessibility to definitive ROP treatment by retina specialists in Colombia. Panel a shows the locations of retina specialists who report having the capability for definitive ROP treatment. Panel b maps the modeled ground travel time to the nearest treatment-capable site using the same treatment thresholds as those in Fig. 3. Panel c summarizes departmental population coverage by category. Panel d presents municipal-level coverage, highlighting geographic gaps in timely access to treatment, particularly in frontier and intermediate municipalities.