



Systematic Review

Impact of Telemedicine on Patient-Centered Outcomes in Pediatric Critical Care: A Systematic Review

Devon M. O'Brien ¹, Anahat K. Dhillon ² and Betty M. Luan-Erfe ^{2,*}¹ Keck School of Medicine, University of Southern California, Los Angeles, CA 90033, USA² Critical Care Medicine, Department of Anesthesiology, University of Southern California, Los Angeles, CA 90033, USA

* Correspondence: betty.erfe@med.usc.edu

Abstract: Background: Pediatric intensive care units (ICUs) face shortages of intensivists, posing challenges in delivering specialized care, especially in underserved regions. While studies on telecritical care in the adult ICU have demonstrated decreased complications and mortality, research on telemedicine in the pediatric ICU setting remains limited. This systematic review evaluates the safety and efficacy of audiovisual telemedicine in pediatric ICUs, assessing patient-centered outcomes when compared to in-person intensivist care. Methods: Two reviewers independently assessed studies from PubMed, MEDLINE (Ovid), Global Health, and EMBASE on the pediatric population in the ICU setting that were provided care by intensivists via telemedicine. Studies without a comparison group of in-person intensivists were excluded. Selected studies were graded using the Newcastle–Ottawa scale and the Levels of Evidence Rating Scale for Therapeutic Studies. Results: Of the 2419 articles identified, 7 met the inclusion criteria. Strong evidence suggested that telemedicine increases access to intensive care. Moderate evidence demonstrated that telemedicine facilitates real-time clinical decision-making, reliable remote clinical assessments, improved ICU process measures (i.e., days on a ventilator, days on antibiotics), and decreased length of stay. Weaker evidence supported that telemedicine decreases complications and mortality. Conclusions: Telemedicine may serve as a promising solution to pediatric ICUs with limited intensivist coverage, particularly in low-resource rural and international settings.



Citation: O'Brien, D.M.; Dhillon, A.K.; Luan-Erfe, B.M. Impact of Telemedicine on Patient-Centered Outcomes in Pediatric Critical Care: A Systematic Review. *Anesth. Res.* **2024**, *1*, 54–66. <https://doi.org/10.3390/anesthres1020007>

Academic Editor: Nobuyasu Komasa

Received: 15 May 2024

Revised: 3 June 2024

Accepted: 28 June 2024

Published: 2 July 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: telemedicine; pediatric; intensive care; disparity; safety; efficacy

1. Introduction

A nationwide shortage of intensivists creates disparities in critical care services, particularly in geographically remote or underserved areas [1–5]. Only 3% of intensivists practice in rural US regions, where 21% of children reside, highlighting disparities in coverage [6]. Moreover, limited skilled pediatric intensivists in resource-constrained pediatric intensive care units (ICUs) may compromise care quality and increase patient mortality [7]. Telemedicine or telecare, which is technology-aided remote healthcare, is a potential solution for overcoming geographical barriers and healthcare inequities. Most high-quality studies on critical care telemedicine were conducted in adult ICU settings and demonstrated reductions in length of stay (LOS), complications, and mortality [8–10]. However, the effect of telemedicine on pediatric intensive care remains an ongoing area of exploration due to unique challenges in treating young patients. It is essential to note that with the novelty of telemedicine, ethical and legal implications are presently ill defined and must be carefully considered, especially for providing care to children [11].

Few studies examined telemedicine as the primary method for delivering safe, effective care to pediatric critical care patients. Studies primarily focused on between-hospital transfers, emergency department consultations, and specialized screening, such as for retinopathy of prematurity or encephalopathy [6,12–14]. Previous systematic reviews

evaluated telemedicine in providing acute care but not in the ICU specifically. For example, a review by Nader et al. analyzed the effect of telemedicine on mortality, transfer, and complication rates and Chagas et al.'s systematic review and meta-analysis explored the effect of telemedicine on length of stay, mortality rates, and family and healthcare staff satisfaction. However, both studies were not specific to the ICU setting and included results from other acute care situations, such as emergency triage, rapid-response encounters, and inter-facility transfers [15,16]. Therefore, prior reviews do not evaluate the impact of telemedicine on important critical care process measures such as antibiotic usage, days on ventilator, and initiation of full enteral feeds.

This systematic review aims to synthesize all available studies on the impact of audiovisual telemedicine in pediatric critical care on the critical care process and outcome measures to identify areas for future investigation. By addressing the knowledge gap in pediatric ICU process measures, our review seeks to provide a comprehensive understanding of how telemedicine can be effectively integrated into pediatric ICUs to improve patient outcomes and care quality.

2. Materials and Methods

This Systematic Review followed the Preferred Reporting Items for Systematic and Meta-Analyses (PRISMA) guidelines [17]. The protocol was registered with International Prospective Register of Systematic Reviews (PROSPERO) under registration number CRD42023475236.

2.1. Search Strategy

Assisted by a trained librarian, we searched PubMed, MEDLINE (Ovid), Global Health, and EMBASE on 10 October 2023 for English-only studies on telemedicine for pediatric critical care populations. Supplementary Materials details the specific search phrase used. We identified gray literature by reviewing Google Scholar and systematic reviews on related topics.

2.2. Inclusion and Exclusion Criteria

Patient Population and Setting: Studies on critically ill pediatric patients under 18 years old treated by pediatric intensivists or neonatologists were included, with no restrictions based on race, gender, socioeconomic status, location, or other demographic factors. All studies conducted outside the ICU setting were excluded (e.g., emergency departments, rapid responses, or pre-transfer consultations).

Study Design: Studies with a formal quantitative method and a control group with in-person intensivists were included. Systematic reviews, review articles, case reports, and abstracts were excluded.

Telemedicine Modality: Selected studies utilized video-based synchronous telemedicine, aligning with modern real-time communication needs in pediatric acute care settings. Studies involving telephone or text-messaging telecommunication were excluded.

Outcomes of Interest: Included studies provided data on the safety and efficacy of care, including access to care, real-time clinical decision-making, the reliability of remote clinical assessments, process measures (e.g., days on ventilator, days to enteral feeding, antibiotic usage), and outcome measures (e.g., LOS, complications, survival). We excluded studies assessing cost, patient-provider satisfaction, or residents' education.

2.3. Study Selection and Data Extraction

Two authors (BE and DO) independently completed the selection process. Reviewers met to rectify any disagreement. Extracted data from selected studies included author, year, location, ICU type, cohort collection year, study design, sample size, staffing model and intensivist availability, statistical analysis, and results.

Data Synthesis: Extracted data were synthesized qualitatively. Quantitative data synthesis was not performed due to the heterogeneity of the study settings, telemedicine infrastructure, and outcomes of interest.

Quality Assessment: The Newcastle–Ottawa scale was used to evaluate the quality of selected articles based on case selections, comparability of cases and controls, and ascertainment of exposure [18]. A high-quality study scored 8 to 9 points, moderate quality scored 6 to 7, and low quality scored 5 or under. The Levels of Evidence Rating Scale for Therapeutic Studies and the Grade Practice Recommendations from the American Society of Plastic Surgeons were subsequently used to assess the quality of the body of evidence, which accounts for the consistency of the results and the quality of individual studies [19].

3. Results

The initial database search yielded 2419 unique publications. Seven articles were ultimately included. Figure 1 details the exclusion reasons.

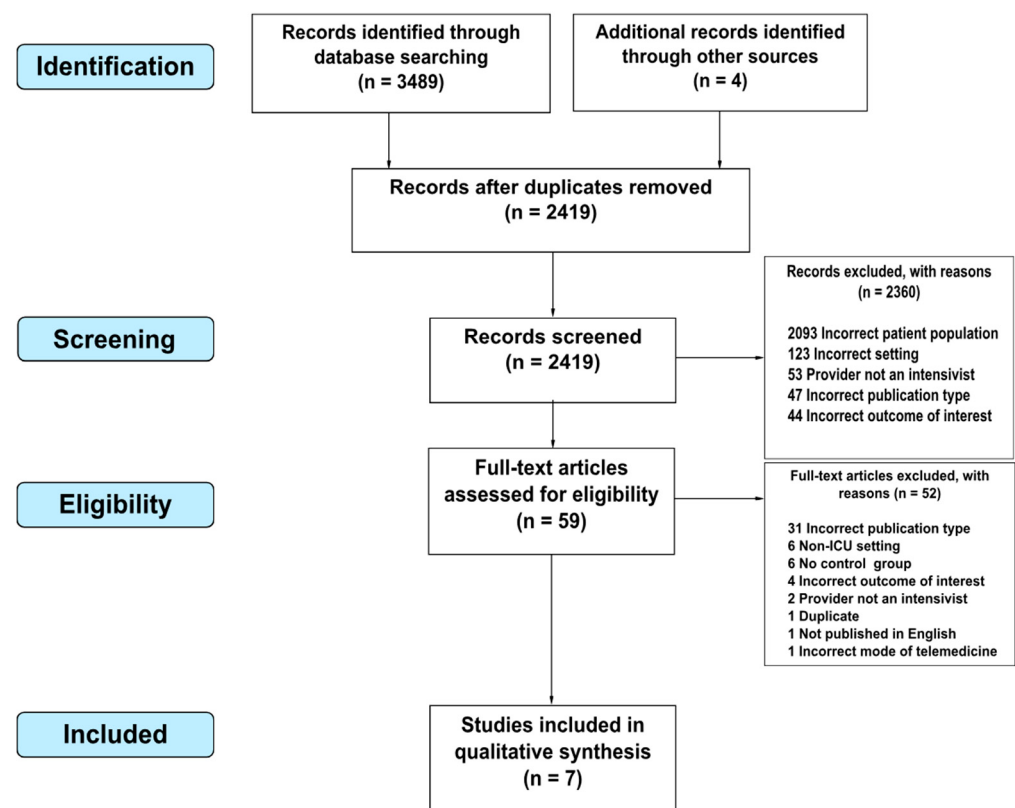


Figure 1. Preferred Reporting Items for Systematic and Meta-Analyses (PRISMA) diagram.

3.1. Study Characteristics

Study Population: The studies included a total of 1138 patients, of which 384 (33.7%) were neonatal ICU (NICU) patients and 754 (66.3%) were pediatric ICU (PICU) patients. All studies were conducted at US-based academic urban hospitals at four NICUs and three PICUs. Makkar et al.'s studies involved telemedicine provided by neonatologists physically located at a US urban Level IV NICU to a rural, medically underserved Level II NICU [20,21]. In Lopez-Magallon et al.'s studies, intensivists at a US tertiary academic center provided telecare to a Colombia-based pediatric cardiac ICU (CICU) [22,23]. Garingo et al.'s studies and the Yager et al. study were conducted solely at a US tertiary academic center [24–26].

Table 1 outlines the study characteristics and results. The studies were conducted between 2007 and 2017.

Table 1. Study characteristics and results.

Author (Year) Location	ICU Type	Setting	Cohort Collection Year	Study Design	# of Patients	Provider Details (Availability and Staffing Model)	Results
Garingo 2012 [24] USA (Los Angeles)	NICU	Urban Domestic	2007–2009	Prospective Comparative Observational	46	6 academic neonatologists matched by training and experience to evaluate for inter-rater agreement.	(1) Excellent agreements (Kappa > 0.75) in patient demographics and vital signs, intermediate-to-good agreements (Kappa: 0.40–0.75) in physical examinations, and poor agreements (Kappa < 0.40) in assessments reliant on a stethoscope. (2) Challenges with radiographic assessment of dilated intestinal loops and auditory and tactile physical exam findings.
Garingo 2016 [25] USA (Los Angeles)	NICU	Urban Domestic	2011–2013	Prospective Comparative Observational	40	Hybrid telemedicine system, with in-person NICU team contacting remote neonatologists for daily rounding and during the day.	(1) Similar LOS, nutrition information, respiratory support, days on antibiotics, phototherapy, and the number of radiologic studies between neonates cared for by on-site and off-site neonatologists.
Lopez-Magallon 2015 [22] USA (Pittsburg), Colombia (Bucaramanga)	CICU	Urban Interna- tional	pre- (2010–2011) and post- (2011–2012) telemedicine groups	Retrospective, pre- and post- intervention	533	Physician-to-physician teleconsultations were made at the request of the local physicians.	(1) Increased access to intensivist care through 156 remote international consultations. (2) 21.8% of teleconsultations resulted in real-time interventions. (3) Statistically significant shortened CICU and hospital LOS. (4) Statistically significant reduced hospital mortality rates.
Lopez-Magallon 2018 [23] USA (Pittsburg), Colombia (Bucaramanga)	CICU	Urban International	pre- (2007–2010) and post- (2011–2015) telemedicine groups	Retrospective, pre- and post- intervention	166	Physician-to-physician teleconsultations were made at the request of the local physicians.	(1) Increased access to intensivist care through 218 remote international consultations. (2) 23.9% of teleconsultations resulted in real-time interventions. (3) Statistically significant longer CICU and hospital LOS. (4) Statistically significant improved hospital survival rates.

Table 1. Cont.

Author (Year) Location	ICU Type	Setting	Cohort Collection Year	Study Design	# of Patients	Provider Details (Availability and Staffing Model)	Results
Makkar 2018 [20] USA (Oklahoma City)	NICU	Urban, Rural Domestic	2013–2015	Retrospective Noninferiority	143	A hybrid telemedicine system with 24/7 neonatal nurse practitioner coverage and daily bedside rounds. Neonatologist physically present 3 days per week and telemedicine coverage other days.	(1) Increased access to care in underserved rural areas. (2) Statistically significant shorter hospital LOS. (3) Statistically significant earlier achievement of full enteral feeds, reduced days on noninvasive ventilation in specific gestational age groups, and lower antibiotic usage beyond 48 h of life. (4) Sepsis incidence rates were similar between groups.
Makkar 2020 [21] USA (Oklahoma City)	NICU	Urban, Rural Domestic	2015–2017	Prospective Noninferiority	155	A hybrid telemedicine system with an in-person neonatal nurse practitioner contacting remote neonatologists when issues arose. Remote neonatologists participated in daily rounding.	(1) Statistically significant earliest achievement of full oral feedings but not days on noninvasive ventilation. (2) Statistically significant shorter hospital LOS.
Yager 2014 [26] USA (Boston)	PICU	Urban Domestic	N/A	Prospective, Randomized	55	55 provider pairings involving 7 attendings and 7 fellows to evaluate for inter-rater agreement.	(1) Substantial to perfect agreement between providers (Kappa = 0.64–1.00) for many aspects of the circulatory and neurologic examinations. (2) Assessments of muscle tone and skin color demonstrated lower agreement (Kappa = 0.23 and Kappa = 0.37, respectively).

CICU, cardiac intensive care unit; ICU, intensive care unit; LOS, length of stay; NICU, neonatal intensive care unit; PICU, pediatric intensive care unit; USA, United States of America.

Study Design: There were four prospective and three retrospective cohort studies, all comparing safety and efficacy between tele- and in-person critical care. Garingo et al., (2012) and Yager et al. investigated inter-rater reliability between remote and in-person intensivists' clinical assessments in the NICU and PICU, respectively [24,26]. Garingo et al., (2016) compared LOS and clinical interventions in the NICU with telemedicine to in-person care [25]. Lopez-Magallon et al.'s studies compared access to care, clinical interventions, LOS, mortality, and survival before and after telemedicine implementation at a Colombia-based pediatric CICU [22,23]. Makkar et al.'s studies compared access to care, clinical interventions, LOS, and complication rates among neonates receiving telecare at a rural US-based NICU with neonates transferred from geographically similar regions who received in-person care [20,21].

Telemedicine Technology: All seven studies utilized telemedicine technologies that facilitated communication between remote intensivists and on-site medical staff, featuring secure data transmission, electronic health record integration, and portable systems with bi-directional real-time audiovisual communication. Garingo et al.'s studies used "RP-7 Remote Presence System" via InTouch Health, featuring digital stethoscope and quick-response cameras. NICU bedside staff underwent four to five hours of training on the telemedicine system to support off-site neonatologists [24,25]. Makkar et al.'s studies used a Polycom video conferencing unit (HDX 7000). On-site nurse practitioners assisted off-site neonatologists during daily telerounds and remote examinations [20,21]. Yager et al.'s telemedicine units featured remote camera control and an electronic stethoscope. Intensivists received training on the system and bedside staff assisted as needed [26]. Lopez-Magallon et al. used a Cisco-based Secure Sockets Layer virtual network and a mobile Dräger physiological monitor system [22,23,27]. Their 2018 study included a 64-h curriculum on telemedicine equipment for bedside nursing staff. Remote intensivists accessed diagnostics such as real-time echocardiography [22,23].

Three studies reported technical issues. Garingo et al., (2012) encountered equipment malfunction (e.g., digital stethoscope), suboptimal audiovisual quality, and internet interruptions [24]. Garingo et al., (2016) reported difficulties in 10% (n = 18) of encounters, citing audiovisual quality issues; two encounters with unresolved connectivity problems delayed telerounds [25]. Yager et al. noted three instances of remote camera zoom malfunction [26].

Telemedicine Staffing: Each intervention featured distinct staffing structures. Garingo et al., (2012) had six neonatologists with telemedicine encounters lasting a median of 13 ± 5 min but did not report in-person encounter duration or frequency [24]. Garingo et al., (2016) described bedside patient encounters lasting five minutes and telemedicine assessments lasting eight minutes ($p = 0.002$) [25]. The study did not describe their neonatologist staffing or encounter frequency. Seven pediatric intensivists and fellows, paired according to experience level, staffed telecare in Yager et al. [26]. The study did not report the duration or frequency of encounters. Lopez-Magallon et al.'s studies conducted daily teleconsultations but did not report the number of intensivists or encounter duration [22,23]. Neonatologists in Makkar et al.'s studies completed daily telerounds and were available 24/7. Makkar et al. did not report the number of intensivists or encounter duration [20,21]. Other studies did not specify remote intensivist availability.

3.2. Outcomes

Access to Care: Four studies demonstrated increased intensive care access with telemedicine. Lopez-Magallon et al., (2015) completed 156 teleconsultations between a US tertiary academic center and a Colombian pediatric CICU. Lopez-Magallon et al., (2018) provided 218 teleconsultations for ECMO patients specifically [22,23]. Makkar et al.'s studies provided telecare to 172 total neonates at a rural US-based NICU [20,21].

Clinical Interventions: Lopez-Magallon et al.'s studies reported real-time interventions in 42 (21.8%) and 64 (23.9%) CICU teleconsultations [22,23]. Interventions included echocardiographic directions, pharmacologic therapy, rhythm or physiology interventions, ventilator parameters, and ECMO weaning trials/adjustments.

Remote Clinical Assessment Reliability: Garingo et al., (2012) and Yager et al. assessed remote clinical evaluation reliability between on- and off-site intensivists in the NICU and PICU, respectively [24,26]. Garingo et al., (2012) showed excellent agreement on demographics and vitals, intermediate-to-good agreement on physical exams, and poor agreement on auditory stethoscope-dependent assessments. Radiographic interpretations showed intermediate-to-good or excellent agreements, except for poor agreement in identifying dilated intestinal loops [24]. Yager et al. demonstrated substantial agreement in some circulatory parameters (e.g., heart rate, capillary refill) and moderate agreement in others (e.g., blood pressure, purpura, pallor). Neurologic assessments showed substantial agreement. Fourteen of fifty-five provider pairs disagreed on muscle tone assessments [26].

Process Measures: Makkar et al. and Garingo et al., (2016) evaluated NICU management outcomes [20,21,25]. Preterm neonates in Makkar et al.'s study (2018) receiving telecare achieved earlier full enteral feeds (33 vs. 34 weeks gestational age (GA), $p = 0.022$), reduced days of noninvasive ventilation (at 34 weeks GA, $p = 0.0321$; 35 weeks GA, $p = 0.0408$), decreased days on oxygen (at 33 weeks GA, $p = 0.0007$; 34 weeks GA, $p = 0.0011$; 35 weeks GA, $p = 0.0005$), and lower antibiotic usage beyond 48 h of life (8% vs. 25%) [20]. Neonates in Makkar et al.'s study (2020) under telecare achieved earlier full enteral feeds (7.43 vs. 12.2 days, $p < 0.001$) and fewer days on noninvasive ventilation, though this was not statistically significant (2.2 vs. 4.16 days, $p = 0.1685$) [21]. Garingo et al., (2016) found no significant differences in NICU process measures between telemedicine and in-person care groups in factors including nutrition (days on total parenteral nutrition or nothing by mouth), respiratory support (days of mechanical ventilation or nasal cannula), days on antibiotics, days requiring peripherally inserted central line or umbilical venous catheter, phototherapy, or number of radiologic studies [25].

Outcome Measures: Three of five articles evaluating LOS showed reduced hospitalization duration with telemedicine compared to in-person care. Lopez-Magallon et al., (2015) demonstrated reduced CICU LOS (6 vs. 11 days, $p < 0.001$) and hospital LOS (22 vs. 28 days, $p < 0.001$), whereas their subsequent 2018 study on ECMO patients showed prolonged CICU LOS (41 vs. 20 days, $p < 0.001$) and hospital LOS (67 vs. 28 days, $p < 0.001$) [22,23]. Makkar et al.'s studies found neonates at the rural hospital receiving telecare had reduced LOS (−2.23 days, 95% confidence interval (CI) 0.46–3.99; −3.01 days, 95% CI 1.1–4.8) (20–21). Garingo et al., (2016) found no difference in LOS (21 vs. 16 days, p nonsignificant) [25].

Makkar et al. (2018) reported comparable sepsis rates among neonates receiving telecare and in-person care (0.45/1000 vs. 0.5/1000 live births) [20]. Lopez-Magallon et al., (2015) demonstrated no significant difference between the pre-telemedicine and post-telemedicine period in pediatric CICU survival rates [22]. Lopez-Magallon et al. (2018) observed increased hospital survival rates for ECMO patients in the post-telemedicine period compared to the pre-telemedicine period (54.1% vs. 29.8%, $p = 0.002$) [23].

3.3. Quality of Included Studies

Table 2 presents the Newcastle–Ottawa scale scores for each study. All studies scored the full 4 points on selection, full 3 points in outcome, and all but one scored the maximum of 2 points on comparability. Garingo et al., (2012) lost one point due to challenges in pairing neonatologists based on experience. All studies received an overall high-quality rating with scores of 8 or 9 points.

Table 2. Newcastle–Ottawa scale assessment of study quality.

Author, Year	Selection	Comparability	Outcome	Total	Quality
Garingo 2012 [24]	4	1	3	8	High
Garingo 2016 [25]	4	2	3	9	High
Lopez-Magallon 2015 [22]	4	2	3	9	High

Table 2. Cont.

Author, Year	Selection	Comparability	Outcome	Total	Quality
Lopez-Magallon 2018 [23]	4	2	3	9	High
Makkar 2018 [20]	4	2	3	9	High
Makkar, 2020 [21]	4	2	3	9	High
Yager, 2014 [26]	4	2	3	9	High

3.4. Strength of Evidence

Table 3 outlines the strength of evidence for patient-centered outcomes. The studies provide Grade A evidence that telemedicine improves access to specialized ICU care for pediatric patients [20–23]. Grade B evidence suggests teleconsultations result in increased clinical interventions and comparable remote clinical assessments [23,24,26]. Grade B evidence supports that telecare may facilitate earlier full enteral feeds, reduced days on noninvasive ventilation in neonates, and possibly decreased ICU LOS [20,21,23,25]. Many outcomes assessed have Grade C evidence, reflecting a lack of studies with similar results, including findings that telemedicine is associated with reduced antibiotic usage, decreased complications like sepsis, and increased survival [20,22,23,25].

Table 3. Grading the body of evidence for patient-centered outcome measures.

Author, Year	Access to Care	Clinical Interventions	Reliability	Enteral Feeding	Ventilator Use	Antibiotic Use	Length of Stay	Complications	Survival
Garingo 2012 [24]			X						
Garingo 2016 [25]					X	X	X		
Lopez-Magallon 2015 [22]	X	X					X		X
Lopez-Magallon 2018 [23]	X	X					X		X
Makkar 2018 [20]	X			X	X	X	X	X	
Makkar, 2020 [21]	X			X	X		X		
Yager, 2014 [26]			X						
Summary of Evidence Quality	(4) Level II	(2) Level II	(2) Level II	(2) Level II	(3) Level II	(2) Level II	(5) Level II	(1) Level II	(2) Level II
Quality of Evidence Body	A	B	B	B	B	C	B	C	C

4. Discussion

Telemedicine infrastructure may improve care for critically ill pediatric patients, particularly those in low-resource settings. There is a growing demand for intensivists to care for patients amidst the rising severity of illnesses and complexity of treatments; however, a nationwide shortage of intensivists exists [2]. Moreover, low- and middle-income countries often lack specialized providers and standardized ICU processes [28]. This systematic review provides strong evidence that telemedicine increases access to pediatric intensive care via remote consultations. Makkar et al.'s and Lopez-Magallon et al.'s studies demonstrated that telemedicine extends intensivist care to underserved communities [20–23]. In Lopez-Magallon et al.'s studies, nearly a quarter of teleconsultations resulted in real-time

interventions [22,23]. Thus, telemedicine effectively brings the expertise of trained intensivists to underserved regions. However, it is critical to recognize that challenges may exist in implementing telemedicine in low-resource and rural regions. Financial infrastructure, digital technology access, and limited high-speed internet connectivity may present significant challenges [29]. Understanding such limitations is necessary to appreciate the balance between the potential of such technology and practical feasibility within the context of pediatric critical care.

The studies provide moderate evidence that telemedicine is associated with reduced LOS, a crucial quality metric in critical care affecting morbidity, mortality, and resource consumption [30–35]. Telemedicine decreases LOS directly and indirectly. Lopez-Magallon et al. (2015) found telecare for pediatric cardiac patients may improve treatment efficacy through early surgical decisions, preventative ECMO cannulation in the operating room, diagnostic changes during echo telemonitoring, and recommendations for catheterization [22]. Where ECMO specialists were scarce in Colombia, telemedicine facilitated the learning curve of ICU centers to acquire expertise and streamline workflow [22]. Telemedicine enabled NICU patients in Makkar et al.'s studies to stay closer to home rather than be transferred to a tertiary center; more mother–infant bonding may have reduced infants' time to full enteral feeding and decreased LOS [20,21]. Adult ICU studies similarly demonstrated reduced LOS [36].

Further research is essential to determine whether telemedicine can not only provide noninferior care to neonates but potentially provide superior care. Although Makkar et al.'s studies were noninferiority studies, infants who were treated locally with telemedicine at the Level II center had superior outcomes compared to infants treated at the higher level center [20,21]. This result is contrary to prior studies showing decreased mortality rates of low-birth-weight infants when treated at a Level III or IV center [37–39]. Makkar et al. attribute this finding to avoiding neonatal stress during hospital transfers, increased family participation, and greater nursing attention at lower-acuity centers [20,21].

Additional research is necessary to evaluate the impact of telemedicine on critical care process measures. Makkar et al. found reduced antibiotic usage, earlier initiation of full enteral feeds, and reduced days on noninvasive ventilation, but Garingo et al., (2016) demonstrated no significant differences in nutrition and respiratory parameters between telemedicine and in-person care [20,21,25]. Other process measures requiring exploration include adherence to ICU best practices, frequency of interdisciplinary rounds, and timeliness of intensivist response [40,41]. Future research should also focus on outcome measures including emergency visits post-discharge, readmission rates, and interhospital ICU-to-ICU transfer rates.

Continued incorporation of modern technologies may help overcome challenges in auditory and tactile aspects of physical examination. Devices such as remote noise-canceling electronic stethoscopes and clinician-worn devices for remote muscle tone assessment may address current limitations [42,43]. Digital retinal imaging compares favorably to bedside indirect ophthalmoscopy in screening for retinopathy of prematurity and has relied on non-physician imagers such as bedside nursing staff trained to capture images for remote ophthalmologists' evaluation [44–46]. The successful application of image-based diagnosis suggests its potential utility in pediatric critical care.

Future research is necessary to further define the safety and efficacy of telemedicine within the pediatric ICU. The heterogeneity of studies on telemedicine in pediatric critical care is evident. The studies utilized different telemedicine technology and intensivist staffing models. Future studies can standardize variables in telemedicine by developing uniform guidelines and protocols for technology use. Establishing standardized metrics or grading systems for evaluating telemedicine platforms within the ICU would also be beneficial. Future studies should provide detailed descriptions such as number and availability of intensivists, training on telemedicine equipment, frequency and duration of encounters, and response time for effective comparison and reproducibility.

Furthermore, this systematic review covered critically ill pediatric patients with diverse medical complexities, age groups, and geographic settings; further studies within each subset are necessary to draw specific conclusions. For instance, variations in prevalent health conditions, sociodemographic backgrounds, and healthcare infrastructure between a Colombia-based pediatric CICU and a rural US-based NICU highlights the need for context-specific research in diverse underserved regions. The absence of studies during the recent pandemic also highlights the need for research on telecare outcomes in a period of increased telemedicine adoption and advancement in the clinical setting [47]. It can be suggested that telemedicine in the pediatric ICU during COVID-19 facilitated continued care of pediatric patients during an international crisis while reducing unnecessary exposure to COVID-19 [48]. However, further research is needed to assess the impact of tele-critical care among children during the COVID-19 pandemic.

While telemedicine may prove useful, it is crucial to acknowledge that in-person patient care remains indispensable in the pediatric ICU setting. The ICU environment requires direct physical interaction for tasks such as completing thorough physical exams, administering treatments, and performing emergency procedures, which telemedicine cannot fully replicate. Thus, while telemedicine enhances pediatric critical care access, in-person care is essential for providing the highest level of immediate, hands-on medical intervention and care. Moreover, ethical and legal ramifications are necessary to consider, including informed consent, physician liability and malpractice risk of remote providers, and laws and regulations for telemedicine [11,49].

Strengths and Limitations

This systematic review utilized multiple reviewers, clear inclusion and exclusion criteria, and documented exclusion reasons to minimize selection bias. The search encompassed diverse studies without restrictions on publication location, ICU type, study quality, or size.

The limitations of this systematic review include the small number of studies meeting the inclusion criteria, which may affect the generalizability of the findings. The heterogeneity of study designs, telemedicine technologies and staffing, and outcome measures further complicate direct comparisons and synthesis of the results. Moreover, the search was limited to English-only studies and four databases, excluding posters and abstracts, potentially contributing to publication bias. These limitations highlight the need for more rigorous, large-scale randomized controlled trials to better understand the impact of telemedicine in pediatric ICU settings.

5. Conclusions

Telemedicine may serve as a promising solution to pediatric ICUs with limited intensivist coverage, particularly in low-resource rural and international settings. This systematic review demonstrates that telemedicine enhances access, reduces LOS, ensures reliable remote assessments, and may improve ICU outcomes for critically ill children. Telemedicine increases access to pediatric intensive care via remote consultations, extending expert intensivist care to underserved communities. The heterogeneity of telemedicine models, including diverse telemedicine technologies and staffing models, highlights the adaptability of telemedicine in various settings. Furthermore, this systematic review covered critically ill pediatric patients with diverse medical complexities, age groups, and geographic settings. Further studies within each subset are necessary to draw specific conclusions and validate the impact of telemedicine on ICU outcome measures, such as complications and mortality. While promising, further research is necessary to validate the impact of telemedicine on ICU among the pediatric patient population. In an era of increased telemedicine adoption following the global pandemic, it is crucial to define how telecritical care may be safely and effectively provided to children.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/anesthres1020007/s1>.

Author Contributions: D.M.O. conceptualized the systematic review, selected and synthesized articles, and drafted the manuscript. A.K.D. reviewed and edited the manuscript. B.M.L.-E. conceptualized the systematic review, selected and synthesized articles, and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors received no financial support for the research, authorship, and/or publication of this article. The authors declare that they have no conflicts of interest.

References

1. Courtright, K.R.; Kerlin, M.P. Intensive care unit staffing and quality of care: Challenges in times of an intensivist shortage. *Rev. Bras. Ter. Intensiv.* **2014**, *26*, 205–207.
2. Halpern, N.A.; Pastores, S.M.; Oropello, J.M.; Kvetan, V. Critical care medicine in the United States: Addressing the intensivist shortage and image of the specialty. *Crit. Care Med.* **2013**, *41*, 2754–2761. [[PubMed](#)]
3. Jatoi, N.N.; Awan, S.; Abbasi, M.; Marufi, M.M.; Ahmed, M.; Memon, S.F.; Farooqui, N.; Khan, M.H.; Saiyid, H.; Husain, A.; et al. Intensivist and COVID-19 in the United States of America: A narrative review of clinical roles, current workforce, and future direction. *Pan Afr. Med. J.* **2022**, *41*, 210. [[PubMed](#)]
4. Diaz, J.V.; Riviello, E.D.; Papali, A.; Adhikari, N.K.J.; Ferreira, J.C. Global Critical Care: Moving Forward in Resource-Limited Settings. *Ann. Glob. Health* **2019**, *85*, 3. [[CrossRef](#)] [[PubMed](#)]
5. Slusher, T.M.; Kiragu, A.W.; Day, L.T.; Bjorklund, A.R.; Shirk, A.; Johannsen, C.; Hagen, S.A. Pediatric Critical Care in Resource-Limited Settings-Overview and Lessons Learned. *Front. Pediatr.* **2018**, *6*, 49. [[CrossRef](#)] [[PubMed](#)]
6. Heath, B.; Salerno, R.; Hopkins, A.; Hertzog, J.; Caputo, M. Pediatric critical care telemedicine in rural underserved emergency departments. *Pediatr. Crit. Care Med.* **2009**, *10*, 588–591.
7. Abdelatif, R.G.; Mohammed, M.M.; Mahmoud, R.A.; Bakheet, M.A.M.; Gima, M.; Nakagawa, S. Characterization and Outcome of Two Pediatric Intensive Care Units with Different Resources. *Crit. Care Res. Pract.* **2020**, *2020*, 5171790. [[CrossRef](#)] [[PubMed](#)]
8. Ramnath, V.R.; Hill, L.; Schultz, J.; Mandel, J.; Smith, A.; Morris, T.; Holberg, S.; Horton, L.E.; Malhotra, A.; Friedman, L.S. An In-Person and Telemedicine “Hybrid” System to Improve Cross-Border Critical Care in COVID-19. *Ann. Glob. Health* **2021**, *87*, 1. [[CrossRef](#)]
9. Ganjali, R.; Jajroudi, M.; Kheirdoust, A.; Darroudi, A.; Alnattah, A. Telemedicine solutions for clinical care delivery during COVID-19 pandemic: A scoping review. *Front. Public Health* **2022**, *10*, 937207.
10. Rosenfeld, B.A.; Dorman, T.; Breslow, M.J.; Pronovost, P.; Jenckes, M.; Zhang, N.; Anderson, G.; Rubin, H. Intensive care unit telemedicine: Alternate paradigm for providing continuous intensivist care. *Crit. Care Med.* **2000**, *28*, 3925–3931.
11. Nittari, G.; Khuman, R.; Baldoni, S.; Pallotta, G.; Battineni, G.; Sirignano, A.; Amenta, F.; Ricci, G. Telemedicine Practice: Review of the Current Ethical and Legal Challenges. *Telemed. J. E-Health* **2020**, *26*, 1427–1437. [[CrossRef](#)]
12. Hayden, E.M.; Samuels-Kalow, M.; Dutta, S.; Cohen, A.; Tune, N.K.; Zachrisson, K.S. Pediatric Patients Discharged After Transfer to a Pediatric Emergency Department: Opportunities for Telehealth? *Ann. Emerg. Med.* **2024**, *83*, 208–213. [[CrossRef](#)] [[PubMed](#)]
13. Brady, C.J.; D’Amico, S.; Campbell, J.P. Telemedicine for Retinopathy of Prematurity. *Telemed. J. E-Health* **2020**, *26*, 556–564. [[CrossRef](#)] [[PubMed](#)]
14. Coffey, R.; Melendi, M.; Cutler, A.K.; Craig, A.K. Telemedicine Consultation to Assess Neonatal Encephalopathy in Rural Community Hospitals and Tertiary Care Centers. *J. Maine Med. Cent.* **2022**, *4*, 7. [[CrossRef](#)]
15. Nadar, M.; Jouvet, P.; Tucci, M.; Toledano, B.; Sicotte, C. Impact of Synchronous Telemedicine Models on Clinical Outcomes in Pediatric Acute Care Settings: A Systematic Review. *Pediatr. Crit. Care Med.* **2018**, *19*, e662–e671. [[CrossRef](#)] [[PubMed](#)]
16. Chagas, M.E.V.; Constant, H.M.R.M.; Jacovas, V.C.; Castro da Rocha, J.; Steimetz, C.G.C.; Matte, M.C.C.; Moreira, T.C.; Cabral, F.C. The use of telemedicine in the PICU: A systematic review and meta-analysis. *PLoS ONE* **2021**, *16*, e0252409.
17. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. PRISMA Group: Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Int. J. Surg.* **2010**, *8*, 336–341. [[CrossRef](#)]
18. Wells, G.A.; Shea, B.; O’Connell, D.; Peterson, J.; Welch, V.; Losos, M.; Tugwell, P. The Newcastle-Ottawa Scale (NOS) for Assessing the Quality of Nonrandomised Studies in Meta-Analyses. 2021. Available online: https://www.ohri.ca/programs/clinical_epidemiology/oxford.asp (accessed on 11 October 2023).
19. Burns, P.B.; Rohrich, R.J.; Chung, K.C. The levels of evidence and their role in evidence-based medicine. *Plast. Reconstr. Surg.* **2011**, *128*, 305–310.
20. Makkar, A.; McCoy, M.; Hallford, G.; Escobedo, M.; Szyld, E. A Hybrid Form of Telemedicine: A Unique Way to Extend Intensive Care Service to Neonates in Medically Underserved Areas. *Telemed. J. E-Health* **2018**, *24*, 717–721.

21. Makkar, A.; McCoy, M.; Hallford, G.; Foulks, A.; Anderson, M.; Milam, J.; Wehrer, M.; Doerfler, E.; Szyld, E. Evaluation of Neonatal Services Provided in a Level II NICU Utilizing Hybrid Telemedicine: A Prospective Study. *Telemed. J. E-Health* **2020**, *26*, 176–183. [\[CrossRef\]](#)
22. Lopez-Magallon, A.J.; Otero, A.V.; Welcher, N.; Bermon, A.; Castillo, V.; Duran, A.; Castro, J.; Munoz, R. Patient Outcomes of an International Telepediatric Cardiac Critical Care Program. *Telemed. J. E-Health* **2015**, *21*, 601–610. [\[CrossRef\]](#)
23. Lopez-Magallon, A.J.; Saenz, L.; Gutierrez, J.L.; Florez, C.X.; Althouse, A.D.; Sharma, M.S.; Duran, A.; Salazar, L.; Munoz, R. Telemedicine in Pediatric Critical Care: A Retrospective Study in an International Extracorporeal Membrane Oxygenation Program. *Telemed. J. E-Health* **2018**, *24*, 489–496. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Garingo, A.; Friedlich, P.; Tesoriero, L.; Patil, S.; Jackson, P.; Seri, I. The use of mobile robotic telemedicine technology in the neonatal intensive care unit. *J. Perinatol.* **2012**, *32*, 55–63. [\[CrossRef\]](#)
25. Garingo, A.; Friedlich, P.; Chavez, T.; Tesoriero, L.; Patil, S.; Jackson, P.; Seri, I. “Tele-rounding” with a remotely controlled mobile robot in the neonatal intensive care unit. *J. Telemed. Telecare* **2016**, *22*, 132–138. [\[CrossRef\]](#)
26. Yager, P.H.; Clark, M.E.; Dapul, H.R.; Murphy, S.; Zheng, H.; Noviski, N. Reliability of circulatory and neurologic examination by telemedicine in a pediatric intensive care unit. *J. Pediatr.* **2014**, *165*, 962–966.e65. [\[CrossRef\]](#)
27. Munoz, R.A.; Burbano, N.H.; Motoa, M.V.; Santiago, G.; Klevemann, M.; Casilli, J. Telemedicine in pediatric cardiac critical care. *Telemed. J. E-Health* **2012**, *18*, 132–136. [\[CrossRef\]](#)
28. Sweigart, J.R.; Aymond, D.; Burger, A.; Kelly, A.; Marzano, N.; McIlraith, T.; Morris, P.; Williams, M.V.; Siegal, E.M. Characterizing Hospitalist Practice and Perceptions of Critical Care Delivery. *J. Hosp. Med.* **2018**, *13*, 6–12. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Top Challenges Impacting Patient Access to Healthcare. 2022. Available online: <https://patientengagementhit.com/news/top-challenges-impacting-patient-access-to-healthcare> (accessed on 31 May 2024).
30. Marcin, J.; Shaikh, U.; Steinhorn, R. Addressing health disparities in rural communities using telehealth. *Pediatr. Res.* **2016**, *79*, 169–176. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Akinkugbe, O.; Cooke, F.J.; Pathan, N. Healthcare-associated bacterial infections in the paediatric ICU. *JAC Antimicrob. Resist.* **2020**, *2*, dlaa066. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Steen, E.H.; Lasa, J.J.; Nguyen, T.C.; Keswani, S.G.; Checchia, P.A.; Anders, M.M. Central Venous Catheter-Related Deep Vein Thrombosis in the Pediatric Cardiac Intensive Care Unit. *J. Surg. Res.* **2019**, *241*, 149–159. [\[CrossRef\]](#)
33. Dervan, L.A.; Di Gennaro, J.L.; Farris, R.W.; Watson, R.S. Delirium in a Tertiary PICU: Risk Factors and Outcomes. *Pediatr. Crit. Care Med.* **2020**, *21*, 21–32. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Marcin, J.P.; Slonim, A.D.; Pollack, M.M.; Ruttimann, U.E. Long-stay patients in the pediatric intensive care unit. *Crit. Care Med.* **2001**, *29*, 652–657. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Pollack, M.M.; Wilkinson, J.D.; Glass, N.L. Long-stay pediatric intensive care unit patients: Outcome and resource utilization. *Pediatrics* **1987**, *80*, 855–860. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Kalvelage, C.; Rademacher, S.; Dohmen, S.; Marx, G.; Benstoem, C. Decision-Making Authority During Tele-ICU Care Reduces Mortality and Length of Stay-A Systematic Review and Meta-Analysis. *Crit. Care Med.* **2021**, *49*, 1169–1181. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Paneth, N.; Kiely, J.L.; Wallenstein, S.; Susser, M. The choice of place of delivery. Effect of hospital level on mortality in all singleton births in New York City. *Am. J. Dis. Child.* **1987**, *141*, 60–64. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Gortmaker, S.; Sobol, A.; Clark, C.; Walker, D.K.; Geronimus, A. The survival of very low-birth weight infants by level of hospital of birth: A population study of perinatal systems in four states. *Am. J. Obstet. Gynecol.* **1985**, *152*, 517–524. [\[CrossRef\]](#)
39. Kamath, B.D.; Box, T.L.; Simpson, M.; Hernandez, J.A. Infants born at the threshold of viability in relation to neonatal mortality: Colorado, 1991 to 2003. *J. Perinatol.* **2008**, *28*, 354–360. [\[CrossRef\]](#)
40. Lilly, C.M.; McLaughlin, J.M.; Zhao, H.; Baker, S.P.; Cody, S.; Irwin, R.S.; UMass Memorial Critical Care Operations Group. A multicenter study of ICU telemedicine reengineering of adult critical care. *Chest* **2014**, *145*, 500–507. [\[CrossRef\]](#)
41. Fortis, S.; Sarrazin, M.V.; Beck, B.F.; Panos, R.J.; Reisinger, H.S. ICU Telemedicine Reduces Interhospital ICU Transfers in the Veterans Health Administration. *Chest* **2018**, *154*, 69–76. [\[CrossRef\]](#)
42. Cruz, F.R.; Magwili, G.V.; Collado, M.R.; Rosario, K.M.; Aguilla, R.M.; Egargue, J.C.C. Electronic Stethoscope with Noise Cancellation for Telehealth Peripheral. In Proceedings of the 3rd International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM), Medan, Indonesia, 16–17 September 2019; pp. 155–159.
43. Brokaw, E.B.; Heldman, D.A.; Plott, R.J.; Rapp, E.J.; Montgomery, E.B.; Giuffrida, J.P. Development of a clinician worn device for the evaluation of abnormal muscle tone. In Proceedings of the 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Chicago, IL, USA, 26–30 August 2014; pp. 4091–4094.
44. Thanos, A.; Yonekawa, Y.; Todorich, B.; Moshfeghi, D.M.; Trese, M. Screening and treatments using telemedicine in retinopathy of prematurity. *Eye Brain* **2016**, *8*, 147–151.
45. Wang, S.K.; Callaway, N.F.; Wallenstein, M.B.; Henderson, M.T.; Leng, T.; Moshfeghi, D.M. SUNDROP: Six years of screening for retinopathy of prematurity with telemedicine. *Can. J. Ophthalmol.* **2015**, *50*, 101–106. [\[CrossRef\]](#)
46. Karp, K.A.; Baumritter, A.; Pearson, D.J.; Pistilli, M.; Nyquist, D.; Huynh, M.; Satnes, K.; Keith, R.; Ying, G.S.; Quinn, G.E. Training retinal imagers for retinopathy of prematurity (ROP) screening. *J. AAPOS* **2016**, *20*, 214–219. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Kichloo, A.; Albosta, M.; Dettloff, K.; Wani, F.; El-Amir, Z.; Singh, J.; Aljadah, M.; Chakinala, R.C.; Kanugula, A.K.; Solanki, S. Telemedicine, the current COVID-19 pandemic and the future: A narrative review and perspectives moving forward in the USA. *Fam. Med. Community Health* **2020**, *8*, e000530. [\[CrossRef\]](#) [\[PubMed\]](#)

-
48. Battineni, G.; Pallotta, G.; Nittari, G.; Amenta, F. Telemedicine framework to mitigate the impact of the COVID-19 pandemic. *J. Taibah Univ. Med. Sci.* **2021**, *16*, 300–302. [[CrossRef](#)] [[PubMed](#)]
 49. Ricci, G.; Gibelli, F.; Bailo, P.; Caraffa, A.M.; Nittari, G.; Sirignano, A. Informed Consent in Paediatric Telemedicine: Challenge or Opportunity? A Scoping Review. *Healthcare* **2023**, *11*, 1430. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.