Seminars in Fetal and Neonatal Medicine 26 (2021) 101201

Contents lists available at ScienceDirect

Seminars in Fetal and Neonatal Medicine

journal homepage: www.elsevier.com/locate/siny

# A systematic review of reports of quality improvement for bronchopulmonary dysplasia

H. Healy [a,b,*], L.E.E. Croonen [c], W. Onland [c], A.H. van Kaam [c], M. Gupta [b]

[a] Boston Children's Hospital, Boston, MA, USA
[b] Beth Israel Deaconess Medical Center, Boston, MA, USA
[c] Emma Children's Hospital Amsterdam University Medical Centers, University of Amsterdam, VU University Medical Center, Amsterdam, the Netherlands

ARTICLE INFO

*Keywords:*
Bronchopulmonary dysplasia
Chronic lung disease
Quality improvement
Prematurity
Neonate
Neonatal intensive care unit

ABSTRACT

Bronchopulmonary dysplasia (BPD) is the most common morbidity of preterm infants, and its incidence has not responded to research and intervention efforts to the same degree as other major morbidities associated with prematurity. The complexity of neonatal respiratory care as well as persistent inter-institutional variability in BPD rates suggest that BPD may be amenable to quality improvement (QI) efforts. We present a systematic review of QI for BPD in preterm infants. We identified 22 reports from single centers and seven from collaborative efforts published over the past two decades. In almost all of the reports, respiratory QI interventions successfully reduced BPD or other key respiratory measures, particularly for infants with birth weight over 1000 g. Several themes and lessons from existing reports may help inform future efforts in both research and QI to impact the burden of BPD.

## 1. The rationale for quality improvement for bronchopulmonary dysplasia

Bronchopulmonary Dysplasia (BPD), formerly known as Chronic Lung Disease (CLD), is one of the most frequent and important sequelae of preterm birth. It is associated with mortality, long-term morbidities, and increased healthcare utilization and cost [1–6]. Advances in maternal and neonatal care have led to major improvements in respiratory care for preterm infants, but high rates of BPD persist. Studies of large cohorts of very low birth weight or very preterm infants from 1993 to 2016 have shown BPD to be among the greatest drivers of morbidity among surviving preterm infants, with some cohorts showing BPD rates to be stable to slightly decreasing over time and others showing BPD rates to be increasing [7–13].

Reasons for our limited progress in preventing or reducing the burden of BPD are unclear. Increasing survival of preterm infants at lower gestational ages has contributed to the changing pathophysiology of BPD and its persistent prevalence. However, rates of other major morbidities associated with extreme prematurity, including late-onset infections, necrotizing enterocolitis (NEC), severe intraventricular hemorrhage (IVH), and severe retinopathy of prematurity (ROP), have decreased in recent decades in tandem with increased survival [8,9,12,14]. What might explain the improvements in these multiple morbidities? Traditionally, major advances and innovations in care are driven by research showing the efficacy of new therapies or care practices. This has been true of neonatal respiratory care, where optimal respiratory support of preterm infants has been defined by epidemiologic studies and large clinical trials that have led to therapeutic advances such as surfactant use, corticosteroid therapy, methylxanthines, and innovative non-invasive and invasive ventilatory strategies [8,15–19]. However, we have learned that knowledge gained from traditional experimental designs is often not sufficient to impact outcomes on a broad scale. Lessons from large randomized control trials may not be applicable to all settings and to all types of NICUs, and when applicable, may not be reliably implemented or implemented correctly. Quality improvement (QI) efforts, built on using experiential models to allow learning over time, are needed to systematically apply generalizable knowledge to local contexts [20]. While QI has become foundational in all areas of health care, the "science of improvement" is particularly important for impacting complex systems with multidimensional outcomes [21]. This would be an appropriate description of neonatal intensive care for very premature infants, and indeed, the importance of QI in the NICU is demonstrated by numerous local and collaborative QI efforts that have led to substantial and sustained improvements in neonatal outcomes [14,22]. It has even been argued that most of the recent improvements

* Corresponding author. Boston Children's Hospital, Boston, MA, USA.
*E-mail addresses:* hhealy@bidmc.harvard.edu (H. Healy), L.E.Croonen@amsterdamumc.nl (L.E.E. Croonen), w.onland@amsterdamumc.nl (W. Onland), a.h.vankaam@amsterdamumc.nl (A.H. van Kaam), mgupta@bidmc.harvard.edu (M. Gupta).

https://doi.org/10.1016/j.siny.2021.101201

Available online 30 January 2021

**Abbreviations**

| | |
|---|---|
| BMV | bag mask ventilation |
| BW | birth weight |
| BPD | bronchopulmonary dysplasia |
| BCPAP | bubble continuous positive airway pressure |
| CLD | chronic lung disease |
| CPAP | continuous positive airway pressure |
| CGA | corrected gestational age |
| CPQCC | California Perinatal Quality Care Collaborative |
| DR | delivery room |
| ELBW | extremely low birth weight |
| ESTHER | Echo-guided Surfactant THERapy |
| $FiO_2$ | fraction of inspired oxygen |
| GA | gestational age |
| HFNC | high flow nasal cannula |
| HFOV | high frequency oscillatory ventilation |
| IVH | intraventricular hemorrhage |
| INSURE | INtubation-SURfactant-Extubation |
| LISA | less invasive surfactant administration |
| LFNC | low flow nasal cannula |
| NCPAP | nasal continuous positive airway pressure |
| NICHD | National Institute of Child Health and Human Development |
| NEC | necrotizing enterocolitis |
| NIPPV | non-invasive positive pressure ventilation |
| NI | nosocomial infection |
| $O_s$ | supplemental oxygen |
| PDA | patent ductus arteriosus |
| PDSA | plan-do-study-act |
| PEEP | positive end expiratory pressure |
| PIP | peak inspiratory pressure |
| PVL: | periventricular leukomalacia |
| PBP | potentially better practice |
| VON | Vermont Oxford Network |

in neonatal morbidities can be attributed to QI rather than research [23].

Several characteristics of BPD may help explain why BPD has been particularly resistant to improvement efforts, whether through traditional research or QI. While many outcomes for premature infants reflect multiple drivers and causal pathways, BPD is especially complex and multimodal. Genetic, biological, clinical, and environmental factors may combine to produce significant patient-level variations in risk and disease that are largely ignored by intervention studies that group premature infants into populations [24]. Simplified definitions of BPD may also limit the applicability of one study to other populations; more precise definitions may better allow for identification and targeting of specific drivers relevant to specific NICUs [25]. The most common definition of BPD has been a need for supplemental oxygen at 36 weeks of corrected gestational age (CGA). Although this definition is easily used and is associated with long-term outcomes, it lacks adjustment for variation in respiratory support practices and lacks adequate discrimination of different BPD phenotypes. New definitions that better assess disease severity and predict long-term prognosis have been developed, and may better support efforts to impact BPD management [4,26–28].

Despite past history, certain aspects of the current epidemiology of BPD suggest that it is amenable to further improvement efforts. Like other conditions, BPD rates vary between institutions; this has been well-established even among institutions with comparable populations and similar resources [29]. This variability in BPD, however, has proven more persistent than for other conditions. In the Vermont Oxford Network (VON), improvements in rates of NEC, IVH, ROP, and late-onset sepsis were accompanied by decreases in variation between centers, while variability in BPD rates remained remarkably consistent [14]. Reducing unwarranted variability in practice or performance between sites has proven an effective driver of improvement [14], and it is likely that this continued variation in BPD reflects unmeasured or unidentified practice differences that could inform future improvement opportunities. Racial and ethnic differences also exist in the management of respiratory distress and pulmonary outcomes. Reports from the California Perinatal Quality Care Collaborative and VON have shown significant differences in respiratory care practices between African American, Hispanic, and White infants [30,31]. While some reports show lower BPD rates in Black or Hispanic preterm infants, a population level study from New York showed substantially higher risks of BPD in extremely preterm Black infants as compared to White infants, particularly when using a fetus-at-risk analysis [32,33]. Racial disparities are largely driven by deficiencies and differences in social and health care systems, and broaden potential areas for intervention to include social determinants of health and structure and design of health care delivery [34].

Impacting BPD will require both research to identify and test therapies and QI to understand how best to adapt those therapies to patient, hospital, and community contexts. To better inform ongoing and future QI efforts, we sought to undertake a systematic review of quality improvement for BPD in premature infants.

**Table 1**
PubMed search terms.

| Concept | PubMed Search Terms |
|---|---|
| Quality Improvement | ((quality improvement[MeSH Terms]) OR (quality improvement) OR (potentially better[Title/Abstract])) |
| AND | AND |
| Bronchopulmonary Dysplasia | ((bronchopulmonary dysplasia[MeSH Terms]) OR (chronic lung disease[MeSH Terms]) OR (lung injury, ventilator induced[MeSH Terms]) OR (bronchopulmonary dysplasia) OR (chronic lung disease) OR (respiratory support)) |
| AND | AND |
| Neonatal Care | ((neonate[MeSH Terms]) OR (infant, newborn[MeSH Terms]) OR (infant, premature[MeSH Terms]) OR (neonat*[Title/Abstract]) OR (infant*[Title/Abstract]) OR ("Intensive Care Units, Neonatal"[MeSH])) |
| Authors' search strategy | |

## 2. Systematic review

### 2.1. Methods

We conducted a systematic search for publications describing QI efforts to address BPD. Search strategies were developed from published systematic reviews, consultation with a medical librarian, and input from QI and BPD experts. The primary search was conducted in PubMed [35] on December 15, 2020; terms used for this search are shown in Table 1. The search was supplemented by manual review of bibliographies and reference lists from published articles.

Two authors (HH and MG) conducted independent reviews of identified publications; titles and abstracts were screened to identify potentially eligible articles, then full texts were reviewed for final determination. Differences regarding classification were discussed and resolved. Articles were included if they reported single-center or multicenter improvement initiatives focused on respiratory care in preterm infants with an explicit focus on BPD, and presented outcomes over time.

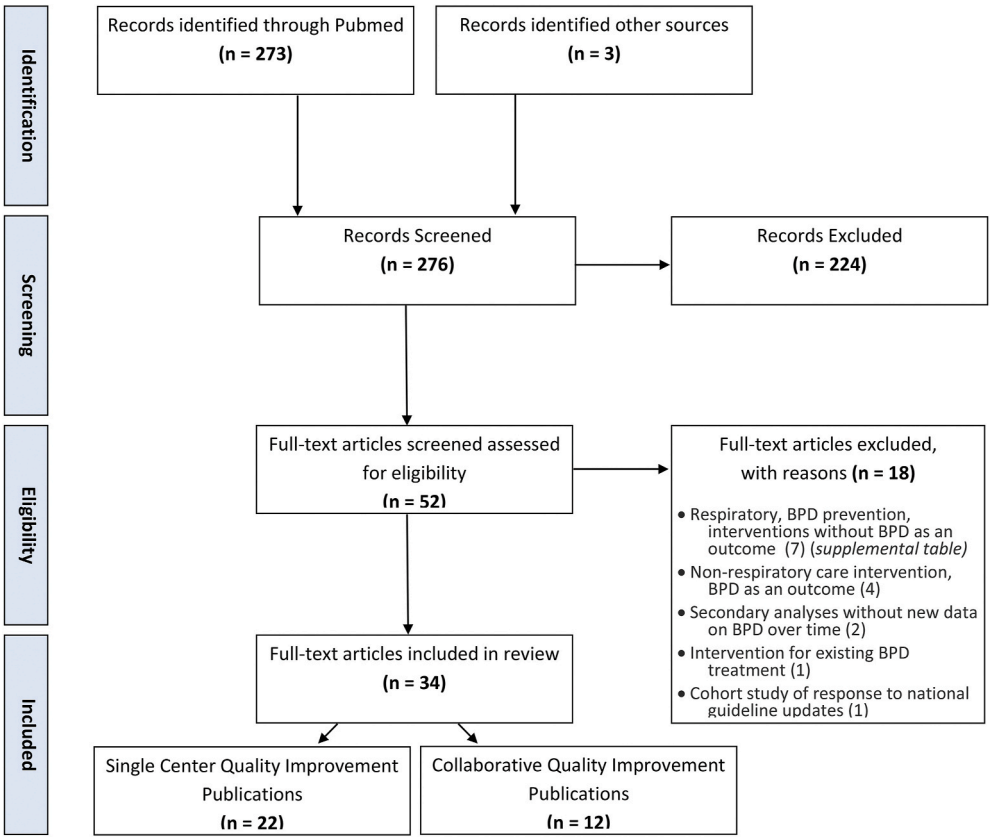


**Fig. 1.** Systematic review flow diagram.

Articles were excluded if they were: not published in English; review articles; retrospective cohort studies examining impact of practice change without an improvement or implementation framework; population-level studies examining impact of national or regional health system changes without description of local improvements; secondary analyses of previously published initiatives; or addressed respiratory care quality improvement but did not report impact on BPD or an equivalent outcome. Articles that focused on interventions in self-described resource limited settings were also excluded; these were deemed to be an important but separate context with unique considerations, and deserving of separate attention.

### 2.2. Systematic review results

The PubMed [35] search identified 273 articles and an additional three were identified through manual review of reference lists, for a total of 276 articles for screening. Of these, 52 were selected for full text review, and 34 were selected for final inclusion (Fig. 1). Among the 18 articles excluded after full text review, seven focused on QI in respiratory care for preterm infants but reported only intermediate outcomes and did not include BPD as an outcome [36–42]; as these may still inform QI efforts focused on BPD prevention, they are described in supplementary materials (Supplementary Table 1).

Of the 34 articles included in the review, 22 were reports from single centers [43–64], and 12 were publications by collaboratives [65–76]. All were published between 2001 and 2020, with 65% published between 2011 and 2020. Collaborative QI was more common earlier and single center QI was more common later; 8 of 12 articles published between 2001 and 2010 were collaborative QI, while 18 of 22 articles published between 2011 and 2020 were single center QI.

### 2.3. Single center QI publications

Table 2 summarizes key features of the 22 single center QI publications. All reports came from level III or level IV units, with a median NICU size of 44 beds (range 10–114). Reported analyses included a median of 290 infants (range 30–1050). Seventeen of the 22 single center units (77%) were within the United States; other units were from France, the Netherlands, Israel, and Canada. Fifteen reports used gestational age inclusion criteria, which ranged from 23 to 33 weeks; 11 used birth weight inclusion criteria, with two centers including infants under 1000 g, one including infants under 1250 g, and the remainder including infants under 1500 g. In general, infants with major congenital anomalies and those who died in the delivery room or before relevant interventions were excluded from reported analyses. Four of the NICUs that reported their single center experience were participants in a larger BPD QI collaborative.

#### 2.3.1. Single center QI methods

The SQUIRE 2.0 guidelines provide a standard framework for reporting quality improvement interventions [77]. Overall, the single center QI articles contained the majority of the elements included in the SQUIRE framework, such as descriptions of the problem, context, interventions, approach to study, and measures to be tracked over time. A notable exception was the category of explicitly-stated specific aims, which were rarely included. Several fundamental aspects of QI were common to many or all of the publications, including: formation of a multidisciplinary improvement team; implementation of evidence-based, potentially better practices; imitation of practices used at other NICUs; and education of unit staff through in-person learning, training modules, and patient simulations.

The use of other methods that are now considered standard for rigorous QI was more varied. Concepts of rapid cycle improvement or Plan-Do-Study-Act (PDSA) cycles first appeared in articles in

**Table 2**
Publications of single center respiratory care quality improvement to reduce bronchopulmonary dysplasia.

| Publication | Year of publication | Participant in Collaborative (Y/N) | Training Program (Y/N)[a] | Unit Size, beds[a] | Country of origin | Time Span | Total # patients | GA inclusion, weeks (wk) | BW inclusion, grams |
|---|---|---|---|---|---|---|---|---|---|
| Jackson [43] | 2003 | Y | Y | 84 | United States | October 1999–July 2001 | 30 | | <1000 g |
| Kaempf [44] | 2003 | Y | N | 44 | United States | 1996–2000 | 290 | | 501–1250 g |
| Birenbaum [45] | 2009 | N | N | 30 | United States | 2002; 2005 | 290 | | 501–1500 g |
| Nowadzky [47] | 2009 | N | N | | United States | 2003–2007 | 317 | | 500–1500 g |
| Levesque [48] | 2011 | N | N | 18 | United States | January 2006–January 2008 | 121 | <33 wk | |
| Mulder [50] | 2012 | N | Y | 24 | Netherlands | 1996–2009 | 382 | 25–29 6/7 wk | |
| Bizzarro [51] | 2014 | N | Y | 54 | United States | January 2004–December 2011 | 700 | | <1500 g |
| Waskosky [52] | 2014 | N | Y | 44 | United States | January 2012–May 2013 | 208 | 28–37 wk | |
| Mola [53] | 2015 | Y | Y | 66 | United States | 2002–2010 | 1050 | 23–29 6/7 wk | |
| Morris [54] | 2015 | N | Y | 67 | United States | 2008–2013 | 349 | <29 wk | |
| Ashmeade [55] | 2016 | N | Y | 82 | United States | December 2007–July 2011 | 295 | <28 wk | <1000 g |
| Birenbaum [46] | 2016 | N | N | 30 | United States | 2002–2013 | 474 | | 501–1500 g |
| Read [56] | 2016 | Y | Y | 44 | Canada | January 2011–January 2013 | 272 | 26–32 6/7 wk | |
| Berneau [57] | 2018 | N | Y | 30 | France | May 2010–April 2016 | 379 | <30 wk | |
| Kubicka [58] | 2018 | N | N | 10 | United States | 2013–2016 | 107 | ≥24 wk | <1500 g |
| Kakkilaya [59] | 2019 | N | Y | 47 | United States | 2014–2017 | 314 | ≤29 wk | |
| Levesque [49] | 2019 | N | N | 21 | United States | January 2012–December 2015 | 149 | <33 wk | |
| Peleg [60] | 2019 | N | Y | | Israel | 2015–2016 | 388 | <33 wk | |
| Raschetti [61] | 2019 | N | Y | 28 | France | 2016 | 217 | ≤32 wk | |
| Tyler [62] | 2019 | N | Y | 30 | United States | January 2014–December 2016 | 186 | | <1500 g |
| Bapat [63] | 2020 | N | Y | 114 | United States | 2012–2018 | | <32 wk | |
| Kim [64] | 2020 | N | Y | 109 | United States | 2016–2019 | 119 | <32 wk | <1500 g |

Publications of quality improvement (QI) to prevent bronchopulmonary dysplasia/chronic lung disease identified by search strategy.
ŧTotal population includes pre and post intervention groups.
[a] When information on status as a training program or unit size was not included in the publication, information was obtained from publically obtained sources or through direct contact with the NICUs. This information was not able to be obtained for all NICUs.

2009–2011. References to the Model for Improvement [78] and tools such as key driver diagrams and Pareto charts have emerged in publications since 2015. We did not find any publications reporting on the use of Six Sigma or Lean methodologies for QI to address BPD.

Data used for QI was typically collected from chart review, staff reporting, or direct observation. Many reports used existing databases such as VON. Most publications, and particularly those published before 2015, used a pre-post model for data analysis, comparing data from before the intervention to data from after the intervention. Some reports included a third epoch of time, either during the implementation of the intervention itself or at a later time to assess for sustainability. Statistical analyses for these reports were most commonly done using traditional methods for comparisons between groups, including Chi-Squared Test, Student's t-test, Fisher's exact text, and the Mann-Whitney *U* test. Logistic regressions were also included in some of the analyses to identify other factors associated with outcomes of interest. Data analysis methods specific to QI, including time-series analysis with run charts or statistical process control charts, appear in ten of the 22 (45%) included publications; all ten were published after 2015. When time-series data analysis was used, it was often done quarterly or semi-annually, depending on the number of patients in each time period, or by individual patient if appropriate for a particular measure.

Nearly all publications reported consideration of human subjects' protection, indicating whether their QI initiative was approved or determined to be exempt by an institutional review board.

### 2.3.2. Single center QI interventions and measures

Table 3 summarizes interventions and measures reported by the 22 single center QI studies. All reported the implementation of multiple, simultaneous interventions through bundles, guidelines, or protocols. Most of the implemented practice changes can be grouped into five categories, described in Table 4: 1) increased and optimized non-invasive ventilation; 2) surfactant delivery; 3) avoidance of hyperoxia; 4) approach to mechanical ventilation; and 5) delivery room based interventions [43–64]. Two centers [46,53] conducted intervention in three of these categories, while five centers [43,44,50,56,60] included two categories and the remaining 15 focused on interventions within one category. Other interventions such as use of caffeine and vitamin A were used as ancillary components in some efforts but were not primary intervention categories.

While all reports used multiple measures for evaluation, most reports did not specifically label the types of measures used. In Table 3 and the following summary, measure category was obtained from the publications when available, and if not, was assigned by the authors of this review. Measures were categorized as outcome, process, or balancing measures. Outcome measures included primary and secondary

**Table 3**
Summary of Methods used in Center Respiratory Care Quality Improvement to Reduce Bronchopulmonary Dysplasia.

| Publication<br>Aim/Goal | Definition of BPD/CLD[a]<br>Population | Intervention(s) [b] | Select Respiratory and Related Measures & Results[c] | Summary of Main Results |
|---|---|---|---|---|
| **Jackson** [43]<br>2003<br>Introduce NIPPV to reduce lung injury | Not stated<br>Infants < 1000 g | Use of NIPPV for infants failing NCPAP, before reintubation; changed nasal prongs from 4 cm to 2.5 cm | O: discharge with $O_2^a$<br>P: frequency of NIPPV use[a], duration of intubation[a], change in $PCO_2$ with NIPPV and with prong change, apnea/bradycardia episodes, reintubation[a]<br>B: staff satisfaction with new protocols[a], subjective assessment of use (secure, skin irritation)[a] | • Decrease in discharge with $O_2$ from 75% to 47%<br>• Increased use of NIV<br>• Decreased duration of intubation<br>• Improvement in staff satisfaction with protocols and subjective assessments |
| **Kaempf** [44]<br>2003<br>Reduce BPD rate by 15% | Need for $O_2$ at 36 wk CGA<br>Infants 501–1250 g, surviving to NICU admission | Low tidal volume resuscitation and ventilation, permissive hypercarbia, increased use of NCPAP, decreased use of dexamethasone, use of supplemental vitamin A | O: BPD[c], mortality[c], BPD severity[c], exposure to dexamethasone (any dose, days, total dose)[a, decreased]<br>P: duration of ventilation[a], duration of NCPAP[a], exposure to vitamin A[a], $CO_2$ levels[a, increased]<br>B: pneumothorax[c], pneumonia[a], exposure to diuretics[c] | • Nonsignificant increase in BPD<br>• Decline in dexamethasone use from 49% to 22%<br>• Increased use of CPAP<br>• Decreased duration of intubation<br>• No change in pneumothorax |
| **Birenbaum** [45]<br>2009<br>Reduce incidence of BPD | Need for $O_2$ at 36 wk CGA<br>Infants with BW 501–1500 g | Early NCPAP (instead of prophylactic intubation and surfactant), BCPAP use, specific intubation and ventilation criteria | O: BPD[a], discharge with $O_2^a$, mortality[c]<br>P: BMV in DR, T-piece resuscitator use[a], CPAP use in DR[a], exposure to surfactant[c,] exposure to caffeine[c], duration of caffeine use[a, decreased], exposure to ventilation[a], duration of ventilation[c], duration of CPAP[c], duration of $O_2^c$, infant weight gain[c]<br>B: pneumothorax/PIE[c], time to full feeding[a] | • Decrease in BPD 46.5%–20.5%<br>• Decreased exposure to and duration of ventilation<br>• No change in duration of CPAP use or $O_2$<br>• No change in pneumothorax or exposure to surfactant |
| **Nowadzky** [47]<br>2009<br>Implement BCPAP to reduce BPD | $O_2$ at 28 d or 36 wk CGA<br>Infants with BW 500–1500 g | Change to use of BCPAP from constant pressure closed circuit CPAP and more frequent mechanical ventilation, use of vitamin A | O: BPD[c]<br>P: any ventilation[a], duration of ventilation[a], ventilation > 6 d[a]<br>B: pneumothorax[c], PDA ligation[c] | • No change in BPD<br>• Decrease in exposure to and duration of ventilation<br>• No change in pneumothorax |
| **Levesque** [48]<br>2011<br>Reduce incidence of BPD with by limiting use of mechanical ventilation and $O_2$ | Need for $O_2$ at 36 wk CGA<br>Infants < 33 wk GA | Exclusive BCPAP, BCPAP in DR, strict intubation/extubation criteria, extended CPAP use to avoid $O_2$ | O: BPD[a], survival to discharge[c], discharge with $O_2^c$<br>P: BCPAP in DR[a], CPAP before ventilation[a], intubation in first 72 hr[a], exposure to surfactant[a, decreased], exposure to caffeine[c], $FiO_2^a$, duration of $O_2^a$, duration of ventilation[a]<br>B: pneumothorax[c], hypotension in first 24 hr[a], medical treatment for PDA[c], surgery for PDA[c] | • Decrease in BPD 17%–8%<br>• Increased CPAP before ventilation<br>• Decreased exposure to surfactant<br>• Decreased duration of ventilation and $O_2$ |
| **Mulder** [50]<br>2012<br>Change respiratory management in DR to reduce BPD | Severity scale, as defined by NICHD Consensus Group<br>Infants < 30 wk GA | Change from elective intubation at birth to early CPAP, allowed higher max CPAP (8 cm $H_2O$), permissive hypercapnia, tidal volume measurement to minimize volutrauma | O: Moderate – severe BPD[a], mortality[c], exposure to postnatal steroids[a, decreased]<br>P: Intubation in first 72 hr[a], any ventilation[a], exposure to surfactant[c], duration of ventilation[c]<br>B: 5 min Apgar score, pneumothorax[c], treatment for PDA[c] | • Decrease in BPD 47%–37%<br>• Decrease in post-natal steroid use 29%–10%<br>• Decrease in exposure to and duration of ventilation<br>• No change in pneumothorax or exposure to surfactant |
| **Bizzarro** [51]<br>2014<br>Reduce BPD and ROP by regulating the use of $O_2$ | Need for $O_2$ at 36 wk CGA and radiographic changes<br>VLBW, inborn and transferred < 48 h | Lowered target SpO2 ranges, new oxygen saturation monitoring system, oxygen blenders added in DR and default $FiO_2$ lowered from 1.0 to 0.4, pulse oximeter use in DR | O: BPD or death[c], ROP or death[c], severe ROP[a], ROP requiring surgery[a], exposure to surfactant[decreased]<br>P: none stated[n]<br>B: 5-min Apgar[c], pneumothorax[c] | • No change in BPD<br>• Decrease in exposure to surfactant<br>• No change in pneumothorax |
| **Waskosky** [52]<br>2014<br>Reduce discharge on $O_2$ by increasing use of non-invasive respiratory support | Not stated<br>Preterm infants ≥ 28 wk GA | Primary respiratory support of CPAP, T-piece resuscitator, use of INSURE, criteria for CPAP, intubation, and wean off $O_2$ | O: Discharge with $O_2^c$, Rate of intubation[c], reintubation in first 10 d[c]<br>P: Rate of CPAP use[a], average duration of ventilation[c], average duration of $O_2^c$<br>B: none stated[n] | • No change in discharge home with oxygen<br>• Increase in CPAP use<br>• No change in duration of ventilation or $O_2$ |
| **Mola** [53]<br>2015<br>Reduce incidence of BPD with respiratory care bundle | Need for $O_2$ at 36 wk CGA<br>Infants 23–29 6/7 wk who survived to intubation | Prophylactic surfactant, vitamin A use, reduced $SpO_2$ alarm limits, $O_2$ blending for nasal cannula, optimized CPAP technique, prevention of unplanned extubation, ventilator wean and escalation protocol, standardized caffeine use | O: BPD-free survival[a,not sustained], $O_2$ at 28 d[a], discharge with $O_2$<br>P: exposure to prophylactic surfactant[a, increased], caffeine[a, increased], postnatal steroids[b, increased], duration of ventilation[a], duration of CPAP[a]<br>B: pneumothorax[c] | • Decrease in BPD 51.2%–29.9% but not sustained at later time<br>• Decrease in O2 at 28 d<br>• Decrease in duration of ventilation<br>• Increase in duration of CPAP |

(*continued on next page*)

**Table 3** (*continued*)

| Publication<br>Aim/Goal | Definition of BPD/CLD[a]<br>Population | Intervention(s) [b] | Select Respiratory and Related Measures & Results[c] | Summary of Main Results |
|---|---|---|---|---|
| **Morris** [54]<br>2015<br>Decrease rate of BPD by forming a Small Baby Unit | Need for $O_2$ at 36 wk CGA<br>Infants < 28 wk GA | Creation of a Small Baby Unit to care for ELBW infants including focus on non-invasive respiratory care, increased use of CPAP, earlier extubation, avoidance of intubation | O: BPD[a], discharge with $O_2^S$, survival without specified morbidities[a]<br>P: Successful extubation > 72 h in first wk[a], exclusive CPAP management[a], resource utilization (radiographs per patient, lab tests)[a, decreased]<br>B: VON composite score of survival without specified morbidities[a], NI[a], growth failure[a] | • Decrease in BPD 47.5%–35.4%<br>• Increased survival<br>• Increase in CPAP use<br>• Decrease in exposure to ventilation<br>• Decrease in composite score of morbidity |
| **Ashmeade** [55]<br>2016<br>Implement golden hour pathway to reduce BPD | Not stated<br>Infants < 28 wk GA or BW < 1000 g | Golden hour protocol, respiratory support standardized, time to surfactant and CPAP emphasized, required proficiency at intubation in DR | O: BPD incidence[c], odds ratio of BPD[a], odds ratio of ROP[a]<br>P: 1 and 5 min Apgar scores[b], time to surfactant[a], $FiO_2$ and $SpO_2$ at admission[c]<br>B: intubation in delivery room[b, increased] | • No change in BPD<br>• Decreased time to surfactant<br>• Increased intubation in delivery room |
| **Birenbaum** [46]<br>2016<br>Test for sustained improvement in BPD and discharge with $O_2$ | Need for $O_2$ at 36 wk CGA<br>Infants with BW 501–1500 g | Continuation of interventions described in Birenbaum 2009 [45], stopped use of prophylactic indomethacin, change of ventilator model, use of volume targeted ventilation, limited use of 1.0 $FiO_2$ in DR | O: BPD[c], discharge with $O_2^a$, mortality[c]<br>P: BMV in DR[a, decreased], CPAP use in DR, intubation in DR[increased], exposure to surfactant[c], CPAP prior to ventilation[b, decreased], ventilation after CPAP[c], exposure to ventilation[c]<br>B: pneumothorax[c], time to full feeding,[a] weight at 28 d[c], time to regain weight[a], IVH[c], PDA[c] | • Decrease in BPD 23%–18% (non-significant)<br>• Decrease in discharge home with $O_2$ 15%–8%<br>• No change in exposure to ventilation<br>• No change in pneumothorax |
| **Read** [56]<br>2016<br>Implement new mechanical ventilation and surfactant guideline to reduce BPD | $O_2$ or respiratory support at 36 wk GA<br>Infants 26–32 6/7 wk | Minimize use of mechanical ventilation, increased CPAP use, use of INSURE method of surfactant administration, specific criteria for respiratory escalation | O: BPD[c], mortality[c]<br>P: exposure to surfactant[c], initial management with CPAP[c], initial management with ventilation and surfactant[a, decreased], INSURE method[a, increased], no respiratory support[c], need for ventilation > 2 h in first wk[a]<br>B: treatment mode failure in first 7 d[c] | • Decrease in BPD 27%–18% (non-significant)<br>• No change in initial management with CPAP<br>• Increase in use of INSURE method<br>• No change in exposure to surfactant |
| **Berneau** [57]<br>2018<br>Reduce BPD by implementing LISA Protocol | Severity scale, as defined by NICHD Consensus Group<br>379 inborn Infants < 30 wk GA | Introduced LISA Protocol | O: survival without moderate-severe BPD at 36 wk CGA/discharge[c], mortality[c], death or major morbidities[c]<br>P: exposure to LISA[a], amount and time of surfactant, $O_2$ at 28 d[a], duration of first ventilation period[a]<br>B: pneumothorax[c], surgery for PDA[c] | • No change in BPD<br>• Decrease in $O_2$ at 28 d<br>• Decrease in duration of first ventilation period<br>• No change in pneumothorax or surgery for PDA |
| **Kubicka** [58]<br>2018<br>Respiratory care bundle to reduce CLD by 10% | $O_2$ or positive pressure at 36 wk CGA<br>VLBW Infants ≥ 24 wk GA | T-piece resuscitator use, NIPPV with RAM starting in DR, intubation/extubation criteria, HFOV as rescue, avoidance of over sedation | O: BPD[a], death or BPD[a], discharge with $O_2^S$, exposure to postnatal steroids[c]<br>P: DR intubation rates[a, decreased], any intubation rate[a, decreased], any use/duration on: HFOV, conventional ventilation[a, decreased], NIPPV[c], CPAP[c], HFNC[a, decreased], LFNC[a, decreased], surfactant administration[a, decreased]<br>B: pneumothorax/PIE[c], medical treatment for PDA[x], surgery for PDA[a], need for vasopressive agents[c] | • Decrease in BPD 43%–12%<br>• Decrease in postnatal steroid use 22%–8%<br>• Decrease in exposure to and duration of ventilation<br>• Decrease in exposure to surfactant<br>• No change in pneumothorax<br>• Decrease in surgery for PDA |
| **Kakkilaya** [59]<br>2019<br>Decrease delivery room intubations by 10% in 12 mo | Need for $O_2$ at 36 wk CGA<br>Infants ≤ 29 wk GA | Focus on BMV and buy-in for noninvasive support, round face masks with $ETCO_2$ detectors, improved use of MRSOP steps, improved documentation | O: BPD[a], delivery room intubation[a], death or BPD[a], exposure to surfactant[a, decreased]<br>P: maximum PIP[c], duration of BMV[c], documentation of reason for intubation<br>B: duration of bradycardia[c], time to NICU admission[b], proportion of infants with hypoglycemia[b] and hypothermia[c] at admission, pneumothorax[c] | • Decrease in BPD 26%–13%<br>• Decrease in intubation in DR<br>• Decrease in exposure to surfactant<br>• No change in pneumothorax |
| **Levesque** [49]<br>2019<br>Reduce incidence of BPD by 50% with respiratory care bundle | Need for $O_2$ at 36 wk CGA<br>VLBW < 33 wk GA | BCPAP use, BCPAP in DR, intubation/extubation criteria, prolonged CPAP to avoid $O_2$, additional steps to optimize BCPAP delivery | O: BPD[a], initial management with CPAP[c], initial CPAP success[a], intubation in first 72 hr[a], use of nasal prongs or mask only[a], nasal cannula use before 34 weeks CGA[a], duration of ventilation[a], $O_2$ days[a]<br>P: compliance with bundle elements[a]<br>B: pneumothorax[c], PDA[a], any ROP[c], steroid use for CLD[c] | • Decrease in BPD 37.% to 16.7%<br>• Increase in CPAP use<br>• Decrease in duration of ventilation and $O_2$<br>• No change in post-natal steroid use<br>• No change in pneumothorax |
| **Peleg** [60]<br>2019<br>Implement Golden Hour protocol | Need for $O_2$ at 36 wk CGA<br>Infants < 33 wk GA | Golden hour protocol, respiratory support with adequate PEEP, limited PIP, use of T-piece resuscitator, avoidance of hyperoxia, surfactant within 2 h if indicated | O: BPD[a], exposure to postnatal steroid[c], mortality[c]<br>P: any ventilation[c], duration of ventilation[c]<br>B: none stated[n] | • Decrease in BPD 12.4%–5.9%<br>• No change in exposure to or duration of ventilation |
| **Raschetti** [61]<br>2019 | NICHD criteria | | O: BPD[c], mortality[c]<br>P: proportion of surfactant-treated neonates | • No change in BPD |

(*continued on next page*)

**Table 3** (*continued*)

| Publication<br>Aim/Goal | Definition of BPD/CLD[a]<br>Population | Intervention(s) [b] | Select Respiratory and Related Measures & Results[c] | Summary of Main Results |
|---|---|---|---|---|
| Reduce time to surfactant to within first 3 h | Infants ≤ 32 wk | Use of ESTHER, surfactant administration when $FiO_2$ or lung ultrasound score exceeded threshold | who received drug in first 3 hr[a], maximal FiO2 before surfactant[c], duration of ventilation[a], duration of CPAP or NIV[c], duration of O2[c], duration ventilator-free[a]<br>B: exposure to surfactant[c] | • Decrease in duration of ventilation<br>• No change in duration of $O_2$<br>• No change in exposure to surfactant |
| **Tyler** [62]<br>2019<br>Reduce discharge on oxygen by 50% over 2 yr | Need for $O_2$ at 36 wk CGA<br>VLBW infants | Standardized room air challenge, used of effective $FiO_2$ table for different delivery methods, standardized $O_2$ delivery method based on CGA, extended CPAP use to avoid $O_2$ | O: BPD[a], discharge with $O_2$[a]<br>P: average CGA to discontinue respiratory support[c]<br>B: CGA at discharge[c], weight at discharge[c], unplanned readmission within 30 d[c] | • Decrease in BPD 31.2%–25.4%<br>• Decrease in discharge with $O_2$ 34.4%–21.7%<br>• No change in CGA at discharge<br>• No change in 30-day readmission rate |
| **Bapat** [63]<br>2020<br>Decrease rate of BPD by 20% over 4 yr | Need for $O_2$ and/or respiratory support at 36 wk CGA<br>Infants < 32 wk GA | Respiratory therapist driven protocol for extubation, revised oxygen saturation guidelines, noninvasive respiratory support protocol, prolonged CPAP to avoid $O_2$ | O: BPD[a], severe BPD[a] ($FiO_2$ > 30% and/or PPV and/or HFNC at 36 wk CGA)<br>P: $O_2$ at 28 d[a], time to first extubation[a], ratio of CPAP to intubated days[a], compliance with $SpO_2$ alarm limits[a]<br>B: skin pressure injuries related to CPAP[a] | • Decrease in BPD by special cause variation<br>• Decrease in severe BPD 57%–29%<br>• Decrease in $O_2$ at 28 d<br>• Decrease in skin pressure injuries related to CPAP |
| **Kim** [64]<br>2020<br>Decrease incidence of BPD by 15% | Need for $O_2$ at 36 wk CGA<br>Infants < 1500 g or < 32 wk GA | Secondary Aims: Administer surfactant within 1 h of intubation for > 90% in 1 yr; Intubate within 90 min of meeting criteria in 2 yr<br>Adjusted intubation criteria, focus on decreasing time to surfactant, decreasing time to intubation when indicated | O: BPD[a]<br>P: time between qualifying for intubation and documented time of intubation[a], time between intubation and surfactant administration[a]<br>B: unilateral surfactant administration[c], malposition endotracheal tube[c], pneumothorax[c] | • Decrease in BPD 28.6%–22.3% and 25.6%–21.8% (at two practice locations)<br>• Decrease in time to surfactant<br>• No change in pneumothorax |

Summary of publications describing quality improvement to reduce bronchopulmonary dysplasia performed by single institutions.
Abbreviations: BMV, bag mask ventilation; BW, birth weight; BPD, bronchopulmonary dysplasia; BCPAP, bubble continuous positive airway pressure; CLD, chronic lung disease; CPAP, continuous positive airway pressure; CGA, corrected gestational age; DR, delivery room; ELBW, extremely low birth weight; ESTHER, Echo-guided Surfactant THERapy; $FiO_2$, fraction of inspired oxygen; GA, gestational age; HFNC, high flow nasal cannula; HFOV, high frequency oscillatory ventilation; IVH, intraventricular hemorrhage; INSURE, INtubation-SURfactant-Extubation; LISA, less invasive surfactant administration; LFNC, low flow nasal cannula; NCPAP, nasal continuous positive airway pressure; NICHD, National Institute of Child Health and Human Development; NEC, necrotizing enterocolitis; NIPPV, non-invasive positive pressure ventilation; NI, nosocomial infection; $O_s$, supplemental oxygen; PDA, patent ductus arteriosus; PEEP, positive end expiratory pressure; PIP, peak inspiratory pressure; PVL, periventricular leukomalacia; PBP, potentially better practice; PEI, pulmonary interstitial emphysema; ROP, retinopathy of prematurity; SpO2, oxygen saturation; VON, Vermont Oxford Network; VLBW, very low birth weight.

[a] Bronchopulmonary dysplasia (BPD) and Chronic Lung Disease (CLD) otherwise indicated only by abbreviation BPD.

[b] All interventions included a component of education and collaborative team work.

[c] Describes measures (O: outcome; P: process; B: balancing), as defined by publication authors if available; otherwise, select pertinent measures were categorized by review authors. Results indicated as: [a]desired effect observed, [b]undesired effect observed, [c]no significant effect observed. Where desired effect may vary by intervention or are not implicit, increased or decreased in outcome occurrence/proportion is indicated. If not specified above, result was not provided in paper. In most cases, additional clinical outcomes (such as IVH, PVL, NEC, ROP, PDA, and infection) were analyzed with pre/post data. These outcomes are not stated above unless these constituted a specific measure per publication authors. Patient characteristics compared over time were not considered as measures.

outcomes. Common outcome measures, in addition to BPD incidence, were mortality (11 of 22 articles, 50%), severe BPD (3 of 22, 14%), and discharge on supplemental oxygen (9 of 22, 41%). Process measures varied the most between interventions; the most common process measures were length (days) of each mode of respiratory support (12 of 22, 55%), and need for intubation and/or any ventilation (9 of 22, 41%). The most common balancing measures were pneumothorax (13 of 22, 59%) and surgery for PDA (5 of 22, 23%).

The definition of BPD varied among the publications. Thirteen of 22 (59%) defined BPD as the need for supplemental oxygen at 36 weeks PMA or at discharge, or a slight variation thereof. Three (14%) publications defined BPD as the need for supplemental oxygen or positive pressure respiratory support at 36 weeks PMA, three (14%) adhered to the graded definition of BPD used by the NICHD, and the remaining three (14%) articles used a different definition or did not state the definition used.

### 2.3.3. *Single center QI results*

Of single center QI efforts, 14 (64%) demonstrated a significant reduction in the incidence of BPD (Table 3). Ten of the 14 (71%) efforts showing improvement in BPD utilized a non-invasive respiratory support type of intervention (Table 4), and seven (50%) of those employed only interventions within the non-invasive respiratory support category. Importantly, among publications that showed a reduction in overall BPD and examined results by subgroups, an impact in the most premature and smallest infants was rarely significant [45,50,58,60]. Among the eight (36%) efforts that did not reduce BPD, five showed improvement in process measures that suggest a better respiratory outcome, such as significantly fewer infants needing any ventilation and fewer ventilation days overall among those that did require ventilation [44,47,56,57,61]. Two articles showed improvement in other respiratory process measures [52,55] and one article focusing on oxygen targeting did not show improvement in respiratory outcomes but did show improvement in ROP [51]. Four of nine articles reporting on discharge with supplemental oxygen showed a significant decrease in this measure [43,45,46,62]. Only one of 11 articles reporting on mortality demonstrated a significant improvement [54]. Of note, this publication reported decreased BPD as well as decreased mortality after the creation of a small baby unit, dedicated exclusively to the care of infants less than 28 weeks GA and born weighing less than 1000 g, and included several non-respiratory interventions as well as improvements in respiratory care.

**Table 4**
Respiratory Care Based Interventions used in Single Center Quality Improvement.

| Category | Description | NICUs including Intervention n, (%) | Publications (Author) |
|---|---|---|---|
| Increase and optimize non-invasive ventilation | Trial of CPAP/NIV before intubation, expedite extubation to CPAP/NIV, improve use of CPAP, NIPPV, NAVA, changes to interface | 14 (64) | Jackson [43], Kaempf [44], Brienbaum [45,46] (2009, 2016), Nowadszky [47], Levesque [48,49] (2011, 2019), Mulder [50], Mola [53], Morris [54], Read [56], Kubicka [58], Bapat [63] |
| Surfactant delivery | Expedite delivery, Use of administration protocols: INSURE, LISA, ESTHER | 6 (27) | Waskosky [52], Mola [53], Read [56], Berneau [57], Raschetti [61], Kim [64] |
| Avoidance of hyperoxia | Adjustment of target $SpO_2$ range, use of oxygen blenders, lowered default FiO2 used in resuscitation | 5 (23) | Bizzaro [51], Mola [53], Birenbaum [46] (2016), Peleg [60], Tyler [62] |
| Approach to mechanical ventilation | Gentle ventilation strategies, volume targeted ventilation, high-frequency ventilation | 3 (14) | Kaempf [44], Mulder [50], Birenbaum [46] 2016 |
| Delivery room based interventions | Golden Hour protocols, use of T-piece resuscitator, staff training | 3 (14) | Ashmeade [55], Kakkilaya [59], Peleg [60] |

Description of five categories of intervention used in quality improvement efforts to reduce bronchopulmonary dysplasia at single institutions, 2000 to 2020. Abbreviations: CPAP, continuous positive airway pressure; ESTHER, Echo-guided Surfactant THERapy; INSURE, INtubation-SURfactant-Extubation INSURE; LISA, less invasive surfactant administration; NIPPV, non-invasive positive pressure ventilation; NIV, non-invasive ventilation.

Process measures used varied substantially across publications, reflecting the different interventions targeted by each. All publications that reported process measures showed improvement in at least one. Among balancing measures, 13 articles reported on pneumothorax, and none showed an increased rate.

### 2.4. Collaborative QI publications

Table 5 describes the 12 included publications of collaborative QI addressing BPD. These 12 publications describe seven unique collaborative efforts from 1994 to 2018. The seven collaborative efforts included four that were exclusively collaborative QI and three trials that compared collaborative QI to control groups [65–76]. All collaboratives took place within the US, with the exception of one collaborative of the Canadian Neonatal Network [72]. Of the six collaboratives in the US, four were efforts organized by VON; one was conducted by the NICHD, and one by the California Perinatal Quality Care Collaborative (CPQCC). Collaboratives included a median of 12 (range 9–20) NICUs.

All collaboratives shared a common basic approach, reflective of the Institute for Healthcare Improvement's Breakthrough Series model for collaborative QI [79]. Consistent with this model, collaboratives encouraged participating centers to develop multidisciplinary improvement teams, provided education in quality improvement methods, and identified potentially better practices (PBPs) as change concepts. NICUs then implemented interventions selected from the PBPs through PDSA cycles, interspaced with learning sessions and collaboration by emails, teleconferences, and in-person meetings. Data sharing on key measures and benchmarking performance among participating units was common. Collaboratives fostered trust and collegiality among participant NICUs, and site visits were described as an important element in six of the seven.

Among collaboratives reporting interventions by individual NICUs, a median of 9 (6–40) PBPs were implemented at participating sites. In collaboratives that identified fewer than 10 PBPs, NICUs implemented most PBPs [65–67], and in collaboratives that identified over 10, centers tended to implement a wider range [70,76,80]. Five of the seven collaboratives published results showing decreased BPD incidence; a sixth collaborative led to publications of successful BPD reduction by some of the participant NICUs, and the final collaborative showed significant improvement in secondary intermediate outcome measures, but not in BPD or survival without BPD.

## 3. Discussion

This review of 34 publications suggests that structured quality improvement efforts focused on reducing BPD can be effective. Nearly 70% of the single center and collaborative reports successfully impacted BPD rates, and many of those that did not see a change in BPD did impact important respiratory care processes. Several themes and conclusions can be drawn from this review that warrant highlighting.

Most QI efforts focused on reducing mechanical ventilation. This is consistent with our understanding of the pathophysiology of BPD, and the central role of ventilator-induced lung injury. The benefits of this focus may extend beyond respiratory outcomes, as even minor reductions in exposure to mechanical ventilation have been shown to be associated with reductions in neurodevelopmental impairment in preterm infants [81,82]. Optimizing non-invasive ventilation and minimizing invasive ventilation are now standard practice in neonatal intensive care; however, the use of mechanical ventilation in preterm infants continues to vary substantially across centers, particularly when examined by race and ethnicity [30]. This variation suggests mechanical ventilation may continue to be an appropriate focus for BPD QI efforts in many NICUs.

Although less common than mechanical ventilation, optimizing surfactant delivery was another common area of focus. As the preferred mode of respiratory support for preterm infants with respiratory distress syndrome has shifted to non-invasive ventilation and avoiding intubation, the appropriate use of surfactant has become less clear. Alternative, less invasive modes of surfactant administration that do not require endotracheal intubation may allow for the benefits of both surfactant treatment and avoidance of mechanical ventilation [83,84]. While neonatal practice may be shifting towards the use of alternative methods of surfactant delivery, numerous methods of surfactant delivery are in use, and current practice varies widely, particularly between international regions [85,86]. This likely represents an important area for ongoing research and QI efforts in the neonatal community.

It is also notable that certain interventions were not commonly addressed in the QI publications. For example, we found no QI efforts targeting standardization of postnatal corticosteroid therapy. This may not be surprising given the many ongoing questions about optimal use and timing of postnatal corticosteroids for the prevention and treatment of BPD [87]. Before QI initiatives are able to target optimizing use of corticosteroids, it is likely that more research will be needed to answer these questions.

With regard to QI methods, it appears that methods for BPD QI initiatives are becoming more rigorous over time. Some publications that met inclusion criteria for the review by self-describing as QI and reporting BPD outcomes over at least two time periods did not use methods that would indicate a learning approach to improvement, and would be considered standard in current improvement science. More recent publications more commonly used such methods, including PDSA cycles, key driver diagrams, Pareto charts, and time-series data analysis. This improvement in the quality of the QI likely matches trends in

**Table 5**
Collaborative quality improvement for bronchopulmonary dysplasia.

| Collaborative | Selected Collaborative QI Methods[b] | Results |
|---|---|---|
| Vermont Oxford Network Neonatal Intensive Care Collaborative Quality (NIC/Q) Project [65]<br>1994–1997<br>10 participant NICUs (4 focused on BPD, 6 focused on NI) | •Multidisciplinary teams, data sharing with benchmarking, site visits, in-person meetings, conference calls<br>•Explicit focus on fostering collegial atmosphere<br>•Common outcome measures<br>•Common PBPs identified, specific PBPs for implementation selected by each NICU | •9 PBP concepts developed<br>•6–9 PBPs implemented at each NICU<br>•Decrease in BPD 43.5 to 31.5%[a]<br>•Decrease in death or BPD 55.9%–47.6%[a]<br>•No change in mortality rate |
| Vermont Oxford Network Neonatal Intensive Care Collaborative Quality (NIC/Q) 2000, Reduce Lung Injury (ReLI) Group [66,67]<br>1990–2001<br>9 participant NICUs | •Team approach, established accountability, practice surveys, site-visits, data sharing and benchmarking sites, resource kit<br>•Creation of patient database<br>•Agreed upon common definition of BPD/CLD<br>•Common primary and secondary goals, outcome and process measures<br>•Common PBPs identified, specific PBPs for implementation selected by each NICU | •9 PBP concepts developed<br>•8–9 PBPs implemented at each NICU<br>•Distinguished 7 implementation strategies<br>•Surveys showed substantial practice variation<br>•Found evidence lacking for intuitive practice strategies and practices at many NICUs including benchmarking sites<br>•Consistency in practice improved outcomes<br>•Identified importance of balancing measures<br>•2 NICUs published single center results [43,44] (described in Tables 2 and 3) |
| Vermont Oxford Network Neonatal Intensive Care Collaborative Quality (NIC/Q) 2002, Breathsavers Group [68,69,73]<br>2001–2003<br>19 participant NICUs (16 centers) | •Common primary and secondary goals<br>•Resource kit, shared care processes and deidentified outcomes data with benchmarking<br>•Fostered a high level of trust between NICUs<br>•Common outcome and implementation [process] measures Common PBPs identified, specific PBPs for implementation selected by each NICU | •Overall decrease in BPD by 27%[a]<br>•Increase in survival without BPD 53.6%–63.4%, aOR 1.86[a]<br>•Decreased BPD at 14 NICUs, increased BPD at 4 NICUs<br>•Improvement sustained over 3 yr<br>•Significant change in process measures<br>•No change in balancing measures<br>•Inspired research study to better define BPD |
| National Institute of Child Health and Human Development Neonatal Research Network Trial of Quality Improvement [70]<br>2001–2004<br>17 participant NICUs (3 top performing NICUs served as benchmark NICUs, 14 randomized to intervention or control) | •Cluster-randomized trial<br>•Multidisciplinary teams attended training session<br>•Intervention NICUs visited benchmark NICU; benchmark centers presented self-assessment of practices responsible for outcomes<br>•Common PBPs identified, specific PBPs for implementation selected by each NICU<br>•Implementation [process measures] tracked | •Intervention group NICUs implemented a mean of 7 (5–13) of 27 identified PBPs<br>•Intervention NICUs achieved change in some [process] measures (duration of ventilation in first 7 d, CPAP use on day 1), but not total ventilation, CPAP or $O_2$ duration<br>•No change in [balancing] measure (pneumothorax)<br>•No difference in rate of BPD-free survival or BPD severity between intervention and control NICUs |
| Canadian Neonatal Network Trial of Quality Improvement [72]<br>2002–2005<br>12 participant NICUs (6 NICUs randomized to reduce BPD, 6 to reduce NI, serving as control group for each other, 5 non-participating comparison NICUs) | •Prospective cluster randomized control trial<br>•Multidisciplinary teams included QI officer<br>•Teams attended workshop<br>•Research committee members visited NICUs Compliance monitored, shared learning via teleconferences<br>•Selected outcome indicators and control chart feedback at 3-mo intervals | •Lower trend of incidence of BPD and combined death or BPD in BPD group than control group[a]<br>•Within BPD group, decrease in BPD 29.4%–24.9%, 1 yr incidence OR change 0.70, [a] and death or BPD 35%–30.7%, 1 yr incidence OR change 0.80[a]<br>•Decreased incidence of NI in both BPD and NI groups |
| California Perinatal Quality Care Collaborative (CPQCC), Delivery Room QI Collaborative [74]<br>2011–2012<br>51 participant NICUs (20 collaborative QI, 31 single center QI) of 95 eligible NICUs | •Prospective cohort study of collaborative QI vs single NICU QI vs non-participant NICUs<br>•Implementation of evidence based bundle for delivery room management<br>•Collaborative and single NICU QI groups provided change package and metrics grid; collaborative group held in-person learning lessons, monthly webcasts and teamwork training with other hospitals, both submitted metrics to CPQCC. | •Reduced aOR of BPD and combined death or BPD in collaborative QI group but not in single NICUs or non-participants<br>•Overall BPD incidence was 23.3% and 23.8% baseline and post-intervention, respectively<br>•Effect pattern was not seen in analysis of mortality, IVH, ROP, or NEC |
| The Pod, subgroup (homeroom) of the Vermont Oxford Network Newborn Improvement Collaborative for Quality [75,76]<br>2010–2018<br>10 participant NICUs | •Multi-morbidity quality improvement effort<br>•Developed evidence based toolkit and PBP implementation matrix, specific PBPs for implementation selected by each NICU<br>•Cultivation of trust and teamwork culture, in-person meetings, site visits, teleconferences, data sharing, process and outcome measure comparisons<br>•Used a composite morbidity-mortality benefit metric for benchmarking Encouraged family integration and Small Baby Team formation | •A mean of 29 (19–40) of 45 PBPs were selected for implementation<br>•Delivery room, respiratory care and infection prevention PBPs were widely implemented<br>•Neuroprotective strategies and formal Small Baby Team formation were least adopted BPPS<br>•By 2018, significant improvement in BPD 48%–40%, late infection, PVL, and discharge weight < 10th percentile[a]<br>•No significant change in mortality, focal intestinal perforation, IVH, NEC, ROP<br>•34% of survivors had zero and 36% had one of eight morbidities |

Summary of seven collaborative quality improvement efforts to reduce bronchopulmonary dysplasia among preterm infants, 2000 to 2020, as described in 12 publications identified by authors' search strategy.

Abbreviations: BPD, bronchopulmonary dysplasia; CLD, chronic lung disease; IHI, Institute for Healthcare Improvement; NICU, neonatal intensive care unit; NIC/Q, Neonatal Intensive Care Collaborative Quality; NI, nosocomial infection; PBP, potentially better practice; QI, quality improvement.

[a] Statistically significant result, $p \leq 0.05$ or significant CI.

[b] Description of collaborative methods does not include quality improvement methods taught by collaborative and used for implementation at each NICU.

## Practice points

- Rigorous methods should be used for quality improvement efforts focused on respiratory care and BPD in preterm infants.
- Process measures that include intermediate outcomes may be effective drivers of rapid cycle improvement.
- Numerous potential better practices can be targeted for possible intervention; local context should guide interpretation of current evidence to inform changes.
- QI collaboratives may be particularly impactful for respiratory and BPD improvement.

improvement work across neonatology, and likely in all of health care. As more rigorous methods continue to be spread and applied, we can hope that future BPD QI efforts will be even more impactful than the experience to date.

An aspect of QI methods that may require particular consideration for QI efforts for BPD is selection of measures. Outcome measures will always be of primary importance, and respiratory care QI should seek to impact BPD rates. However, the QI initiatives reviewed used several different BPD definitions; further QI efforts will be strengthened by a universal definition of BPD with diagnostic and prognostic accuracy [26,27]. Furthermore, regardless of definition used, time-series analysis of BPD rates will require long time periods to allow for adequate power to detect changes in performance, in all but the largest NICUs. This is evidenced by the use of quarterly or semi-annual intervals for outcome reporting in most of the BPD QI publications. In addition, the diagnosis of BPD is made weeks to months after most improvement interventions, such as those focused on delivery room care, surfactant administration, or non-invasive ventilation. QI is generally most effective when it is built on iterative tests of change, and is supported by data that can be measured frequently and in real-time to assess the impact of those changes. Thus, BPD alone, as an outcome measure, may be limited in its ability to guide QI efforts. Process measures therefore become even more important. Process measures that are more closely linked to interventions can serve as more effective drivers of improvement, and process measures that are closely linked to outcomes can serve as substitutes for outcome measures as the primary targets of improvement efforts. For BPD, the latter could include process measures related to minimizing ventilator-induced lung injury. Many of the articles reviewed effectively used such measures, including any mechanical ventilation, time to first extubation, failure of first extubation, length of mechanical ventilation, and length of non-invasive ventilation. It is notable that process measures varied substantially across existing publications; developing validated and standardized process measures for respiratory care of preterm infants may strengthen future BPD QI efforts and allow for more robust comparisons of interventions.

A potentially concerning finding is that QI efforts may have had less benefit for BPD reduction in infants at highest risk, those infants under 28 weeks gestation or with birth weight less than 1000 g [44,45,55,58,60]. If this continues to be seen in larger BPD QI initiatives, it may suggest that commonly chosen interventions are less effective in this specific population, and new research and new approaches to intervention may be needed. It is notable that an initiative that used more comprehensive, multisystem interventions, the development of a small baby unit, did reduce BPD in their smallest infants, and it may be that QI efforts targeting this population need to be broadened beyond improvements specific to respiratory care [54]. Although not reviewed here, it is also possible that QI efforts targeting other aspects of neonatal intensive care such as nutrition and infection can help improve respiratory outcomes.

Finally, collaborative QI may have particular value for BPD improvement. While single center publications became more common than collaborative publications over time, the collaboratives consistently showed the ability to impact respiratory practices and outcomes in multiple NICUs. Collaboratives have been well-established in health care QI, and have shown impact in a broad range of health care settings [88]. The BPD QI collaboratives relied on established collaborative QI methods, including group learning, site visits, common measures, data sharing, and benchmarking [79]. Collaborative learning may be especially important for neonatal respiratory care, where nuances of care surrounding a particular strategy, learned through experience, may be as important as the strategy itself. For example, while most centers will strive to use non-invasive ventilation as a primary mode of support, some centers are far more successful than others. This variation may be due to aspects of care that are difficult to define or describe, but perhaps could be observed through site visits or learned through multidisciplinary team collaboration. It is notable that six of the identified collaboratives were led by national organizations, while one was in a single US state. Smaller, regional collaboratives may be especially promising for neonatal respiratory care, as collaboration between NICUs in a relatively small geographic area may facilitate group meetings, site visits, data sharing, and mutual support. State-based perinatal quality collaboratives (PQCs) have become widespread in the U.S., although notably, BPD has generally not been a focus area of these groups to date [89,90]. If regional collaboratives turn their attention to neonatal respiratory care, they may be able to offer new and valuable insight into effective strategies for reducing the burden of BPD in preterm infants.

An important limitation of this review is the substantial likelihood of publication bias. QI efforts that yield a change in outcome are more likely to be published than QI efforts that do not result in improvement [91]. At present, methods for formal assessment of publication bias in QI have not been developed; such methods would be an important contribution to future systematic QI reviews. While there are likely valuable lessons to be learned from unpublished BPD QI efforts, the lessons described above from the published projects should still be informative for NICUs seeking to improve respiratory care and outcomes.

## 4. Conclusions

BPD is the most prevalent morbidity of prematurity, and has proven stubbornly persistent. Decades of research have led to new therapies and new approaches to respiratory support for preterm infants; quality improvement can provide systematic approaches to implementing these practices, and to learning optimal strategies for adapting care to local context. Single center and collaborative QI have already proven effective for impacting BPD in a relatively limited number of reports; it now falls to the larger neonatology community to learn from these experiences and make future BPD QI efforts even more impactful.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.siny.2021.101201.

## References


[1] Ehrenkranz RA, Walsh MC, Vohr BR, Jobe AH, Wright LL, Fanaroff AA, et al. Validation of the national institutes of health consensus definition of bronchopulmonary dysplasia. Pediatrics 2005;116:1353–60.
[2] Guaman MC, Gien J, Baker CD, Zhang H, Austin ED, Collaco JM. Point prevalence, clinical characteristics, and treatment variation for infants with severe bronchopulmonary dysplasia. Am J Perinatol 2015;32:960–7.
[3] Gien J, Kinsella J, Thrasher J, Grenolds A, Abman SH, Baker CD. Retrospective analysis of an interdisciplinary ventilator care program intervention on survival of infants with ventilator-dependent bronchopulmonary dysplasia. Am J Perinatol 2017;34:155–63.
[4] Abman SH, Collaco JM, Shepherd EG, Keszler M, Cuevas-Guaman M, Welty SE, et al. Interdisciplinary care of children with severe bronchopulmonary dysplasia. J Pediatr 2017;181:12–28 e1.
[5] Smith VC, Zupancic JA, McCormick MC, Croen LA, Greene J, Escobar GJ, et al. Rehospitalization in the first year of life among infants with bronchopulmonary dysplasia. J Pediatr 2004;144:799–803.
[6] Beam AL, Fried I, Palmer N, Agniel D, Brat G, Fox K, et al. Estimates of healthcare spending for preterm and low-birthweight infants in a commercially insured population: 2008-2016. J Perinatol 2020;40:1091–9.
[7] Lemons JA, Bauer CR, Oh W, Korones SB, Papile LA, Stoll BJ, et al. Very low birth weight outcomes of the national institute of child health and human development neonatal research network, january 1995 through december 1996. Nichd neonatal research network. Pediatrics 2001;107:e1.
[8] Stoll BJ, Hansen NI, Bell EF, Walsh MC, Carlo WA, Shankaran S, et al. Trends in care practices, morbidity, and mortality of extremely preterm neonates. J Am Med Assoc 2015;314:1039–51. 1993-2012.
[9] Horbar JD, Carpenter JH, Badger GJ, Kenny MJ, Soll RF, Morrow KA, et al. Mortality and neonatal morbidity among infants 501 to 1500 grams from 2000 to 2009. Pediatrics 2012;129:1019–26.
[10] Fellman V, Hellström-Westas L, Norman M, Westgren M, Källén K, Lagercrantz H, et al. One-year survival of extremely preterm infants after active perinatal care in Sweden. J Am Med Assoc 2009;301:2225–33.
[11] Shah PS, Sankaran K, Aziz K, Allen AC, Seshia M, Ohlsson A, et al. Outcomes of preterm infants <29 weeks gestation over 10-year period in Canada: a cause for concern? J Perinatol 2012;32:132–8.
[12] Lui K, Lee SK, Kusuda S, Adams M, Vento M, Reichman B, et al. Trends in outcomes for neonates born very preterm and very low birth weight in 11 high-income countries. J Pediatr 2019;215:32–40 e14.
[13] Nakashima T, Inoue H, Sakemi Y, Ochiai M, Yamashita H, Ohga S, et al. Trends in bronchopulmonary dysplasia among extremely preterm infants in Japan. J Pediatr 2020. 2003-2016.
[14] Horbar JD, Edwards EM, Greenberg LT, Morrow KA, Soll RF, Buus-Frank ME, et al. Variation in performance of neonatal intensive care units in the United States. JAMA Pediatr 2017;171:e164396.
[15] Bancalari E, Claure N, Sosenko IR. Bronchopulmonary dysplasia: changes in pathogenesis, epidemiology and definition. Semin Neonatol 2003;8:63–71.
[16] Jensen EA. Prevention of bronchopulmonary dysplasia: a summary of evidence-based strategies. NeoReviews 2019;20:e189–201.
[17] Owen LS, Manley BJ, Davis PG, Doyle LW. The evolution of modern respiratory care for preterm infants. Lancet 2017;389:1649–59.
[18] Jobe AH, Bancalari E. Bronchopulmonary dysplasia. Am J Respir Crit Care Med 2001;163:1723–9.
[19] van Kaam AH, De Luca D, Hentschel R, Hutten J, Sindelar R, Thome U, et al. Modes and strategies for providing conventional mechanical ventilation in neonates. Pediatr Res 2019:1–6.
[20] Batalden PB, Davidoff F. What is "quality improvement" and how can it transform healthcare? Qual Saf Health Care 2007;16:2–3.
[21] Berwick DM. The science of improvement. J Am Med Assoc 2008;299:1182–4.
[22] Ellsbury DL, Clark RH. Does quality improvement work in neonatology improve clinical outcomes? Curr Opin Pediatr 2017;29:129–34.
[23] Spitzer AR. Has quality improvement really improved outcomes for babies in the neonatal intensive care unit? Clin Perinatol 2017;44:469–83.
[24] Onland W, Hutten J, Miedema M, Bos LD, Brinkman P, Maitland-van der Zee AH, et al. Precision medicine in neonates: future perspectives for the lung. Front Pediatr 2020;8:586061.
[25] Lorch SA. A decade of improvement in neonatal intensive care: how do we continue the momentum? JAMA Pediatr 2017;171:e164395.
[26] Bancalari E, Jain D. Bronchopulmonary dysplasia: can we agree on a definition? Am J Perinatol 2018;35:537–40.
[27] Jensen EA, Dysart K, Gantz MG, McDonald S, Bamat NA, Keszler M, et al. The diagnosis of bronchopulmonary dysplasia in very preterm infants. An evidence-based approach. Am J Respir Crit Care Med 2019;200:751–9.
[28] Isayama T, Lee SK, Yang J, Lee D, Daspal S, Dunn M, et al. Revisiting the definition of bronchopulmonary dysplasia: effect of changing panoply of respiratory support for preterm neonates. JAMA Pediatr 2017;171:271–9.
[29] Van Marter LJ, Allred EN, Pagano M, Sanocka U, Parad R, Moore M, et al. Do clinical markers of barotrauma and oxygen toxicity explain interhospital variation in rates of chronic lung disease? The neonatology committee for the developmental network. Pediatrics 2000;105:1194–201.
[30] Boghossian NS, Geraci M, Lorch SA, Phibbs CS, Edwards EM, Horbar JD. Racial and ethnic differences over time in outcomes of infants born less than 30 weeks' gestation. Pediatrics 2019:144.
[31] Profit J, Gould JB, Bennett M, Goldstein BA, Draper D, Phibbs CS, et al. Racial/ethnic disparity in nicu quality of care delivery. Pediatrics 2017;140:e20170918.
[32] Travers CP, Carlo WA, McDonald SA, Das A, Ambalavanan N, Bell EF, et al. Racial/ethnic disparities among extremely preterm infants in the United States from 2002 to 2016. JAMA Netw Open 2020;3:e206757.
[33] Janevic T, Zeitlin J, Auger N, Egorova NN, Hebert P, Balbierz A, et al. Association of race/ethnicity with very preterm neonatal morbidities. JAMA Pediatr 2018;172:1061–9.
[34] Burris HH, Hwang SS, Collins Jr JW, Kirpalani H, Wright CJ. Re-conceptualizing associations between race and morbidities of extreme prematurity. J Pediatr 2019;207:10–14 e1.
[35] Pubmed [internet]. Bethesda (md): national library of medicine (us). 1946. https://www.Ncbi.Nlm.Nih.Gov/pubmed/ [cited 2021 jan 01]. Available from:.
[36] Hughes JL, McCall E, Alderdice F, Jenkins J. More and earlier surfactant for preterm infants. Arch Dis Child Fetal Neonatal Ed 2006;91:F125–6.
[37] Bookman L, Troy R, McCaffrey M, Randolph G. Using quality-improvement methods to reduce variation in surfactant administration. Qual Saf Health Care 2010;19:e23.
[38] Deuber C, Abbasi S, Schwoebel A, Terhaar M. The toxigen initiative: targeting oxygen saturation to avoid sequelae in very preterm infants. Adv Neonatal Care 2013;13:139–45.
[39] Nzegwu NI, Mack T, DellaVentura R, Dunphy L, Koval N, Levit O, et al. Systematic use of the ram nasal cannula in the yale-new haven children's hospital neonatal intensive care unit: a quality improvement project. J Matern Fetal Neonatal Med 2015;28:718–21.
[40] Weber CD. Applying adult ventilator-associated pneumonia bundle evidence to the ventilated neonate. Adv Neonatal Care 2016;16:178–90.
[41] Chen CY, Chou AK, Chen YL, Chou HC, Tsao PN, Hsieh WS. Quality improvement of nasal continuous positive airway pressure therapy in neonatal intensive care unit. Pediatr Neonatol 2017;58:229–35.
[42] Hoyle ES, Patino F, Yoxall CW. Quality improvement programme to improve compliance with initial respiratory support guideline at preterm birth. Acta Paediatr 2020;109:943–7.
[43] Jackson JK, Vellucci J, Johnson P, Kilbride HW. Evidence-based approach to change in clinical practice: introduction of expanded nasal continuous positive airway pressure use in an intensive care nursery. Pediatrics 2003;111:e542–7.
[44] Kaempf JW, Campbell B, Sklar RS, Arduza C, Gallegos R, Zabari M, et al. Implementing potentially better practices to improve neonatal outcomes after reducing postnatal dexamethasone use in infants born between 501 and 1250 grams. Pediatrics 2003;111:e534–41.
[45] Birenbaum HJ, Dentry A, Cirelli J, Helou S, Pane MA, Starr K, et al. Reduction in the incidence of chronic lung disease in very low birth weight infants: results of a quality improvement process in a tertiary level neonatal intensive care unit. Pediatrics 2009;123:44–50.
[46] Birenbaum HJ, Pfoh ER, Helou S, Pane MA, Marinkovich GA, Dentry A, et al. Chronic lung disease in very low birth weight infants: persistence and improvement of a quality improvement process in a tertiary level neonatal intensive care unit. J Neonatal Perinatal Med 2016;9:187–94.
[47] Nowadzky T, Pantoja A, Britton JR. Bubble continuous positive airway pressure, a potentially better practice, reduces the use of mechanical ventilation among very low birth weight infants with respiratory distress syndrome. Pediatrics 2009;123:1534–40.
[48] Levesque BM, Burnham L, Cardoza N, Adams M, Cohen R, Mirochnick M, et al. Improving respiratory support practices to reduce chronic lung disease in premature infants. Pediatr Qual Saf 2019;4:e193.
[49] Levesque BM, Kalish LA, LaPierre J, Welch M, Porter V. Impact of implementing 5 potentially better respiratory practices on neonatal outcomes and costs. Pediatrics 2011;128:e218–26.
[50] Mulder EE, Lopriore E, Rijken M, Walther FJ, te Pas AB. Changes in respiratory support of preterm infants in the last decade: are we improving? Neonatology 2012;101:247–53.
[51] Bizzarro MJ, Li FY, Katz K, Shabanova V, Ehrenkranz RA, Bhandari V. Temporal quantification of oxygen saturation ranges: an effort to reduce hyperoxia in the neonatal intensive care unit. J Perinatol 2014;34:33–8.
[52] Waskosky A, Huey TK. Quality improvement project: implementing guidelines supporting noninvasive respiratory management for premature infants. Neonatal Netw 2014;33:245–53.
[53] Mola SJ, Annibale DJ, Wagner CL, Hulsey TC, Taylor SN. Nicu bedside caregivers sustain process improvement and decrease incidence of bronchopulmonary dysplasia in infants < 30 weeks gestation. Respir Care 2015;60:309–20.
[54] Morris M, Cleary JP, Soliman A. Small baby unit improves quality and outcomes in extremely low birth weight infants. Pediatrics 2015;136:e1007–15.
[55] Ashmeade TL, Haubner L, Collins S, Miladinovic B, Fugate K. Outcomes of a neonatal golden hour implementation project. Am J Med Qual 2016;31:73–80.
[56] Read B, Lee DS, Fraser D. Evaluation of a practice guideline for the management of respiratory distress syndrome in preterm infants: a quality improvement initiative. Paediatr Child Health 2016;21:4–9.
[57] Berneau P, Nguyen Phuc Thu T, Pladys P, Beuchee A. Impact of surfactant administration through a thin catheter in the delivery room: a quality control chart analysis coupled with a propensity score matched cohort study in preterm infants. PloS One 2018;13:e0208252.
[58] Kubicka Z, Zahr E, Rousseau T, Feldman HA, Fiascone J. Quality improvement to reduce chronic lung disease rates in very-low birth weight infants: high compliance with a respiratory care bundle in a small nicu. J Perinatol 2018;38:285–92.
[59] Kakkilaya V, Jubran I, Mashruwala V, Ramon E, Simcik VN, Marshall M, et al. Quality improvement project to decrease delivery room intubations in preterm infants. Pediatrics 2019;143:1–10.

[60] Peleg B, Globus O, Granot M, Leibovitch L, Mazkereth R, Eisen I, et al. Golden hour" quality improvement intervention and short-term outcome among preterm infants. J Perinatol 2019;39:387–92.
[61] Raschetti R, Yousef N, Vigo G, Marseglia G, Centorrino R, Ben-Ammar R, et al. Echography-guided surfactant therapy to improve timeliness of surfactant replacement: a quality improvement project. J Pediatr 2019;212. 137-43.e1.
[62] Tyler MD, Singh N, McNally MJ, Homa KA, Zbehlik AJ. Improved outcomes with standardized convalescent preterm respiratory care practices. Respir Care 2019;64: 1109–15.
[63] Bapat R, Nelin L, Shepherd E, Ryshen G, Elgin A, Bartman T. A multidisciplinary quality improvement effort to reduce bronchopulmonary dysplasia incidence. J Perinatol 2020;40:681–7.
[64] Kim JE, Brewer M, Spinazzola R, Wallace E, Casatelli J, Beachy J, et al. A quality improvement project to standardize surfactant delivery in the era of noninvasive ventilation. Pediatr Qual Saf 2020;5:e311.
[65] Horbar JD, Rogowski J, Plsek PE, Delmore P, Edwards WH, Hocker J, et al. Collaborative quality improvement for neonatal intensive care. Nic/q project investigators of the Vermont oxford network. Pediatrics 2001;107:14–22.
[66] Burch K, Rhine W, Baker R, Litman F, Kaempf JW, Schwarz E, et al. Implementing potentially better practices to reduce lung injury in neonates. Pediatrics 2003;111: e432–6.
[67] Sharek PJ, Baker R, Litman F, Kaempf J, Burch K, Schwarz E, et al. Evaluation and development of potentially better practices to prevent chronic lung disease and reduce lung injury in neonates. Pediatrics 2003;111:e426–31.
[68] Payne NR, LaCorte M, Karna P, Chen S, Finkelstein M, Goldsmith JP, et al. Reduction of bronchopulmonary dysplasia after participation in the breathsavers group of the Vermont oxford network neonatal intensive care quality improvement collaborative. Pediatrics 2006;118(Suppl 2):S73–7.
[69] Payne NR, LaCorte M, Sun S, Karna P, Lewis-Hunstiger M, Goldsmith JP. Evaluation and development of potentially better practices to reduce bronchopulmonary dysplasia in very low birth weight infants. Pediatrics 2006;118 (Suppl 2):S65–72.
[70] Walsh M, Laptook A, Kazzi SN, Engle WA, Yao Q, Rasmussen M, et al. A cluster-randomized trial of benchmarking and multimodal quality improvement to improve rates of survival free of bronchopulmonary dysplasia for infants with birth weights of less than 1250 grams. Pediatrics 2007;119:876–90.
[71] Lee SK, Aziz K, Singhal N, Cronin CM. The evidence-based practice for improving quality method has greater impact on improvement of outcomes than dissemination of practice change guidelines and quality improvement training in neonatal intensive care units. Paediatr Child Health 2015;20:1–9.
[72] Lee SK, Aziz K, Singhal N, Cronin CM, James A, Lee DS, et al. Improving the quality of care for infants: a cluster randomized controlled trial. CMAJ (Can Med Assoc J) 2009;181:469–76.
[73] Payne NR, Finkelstein MJ, Liu M, Kaempf JW, Sharek PJ, Olsen S. Nicu practices and outcomes associated with 9 years of quality improvement collaboratives. Pediatrics 2010;125:437–46.
[74] Lapcharoensap W, Bennett MV, Powers RJ, Finer NN, Halamek LP, Gould JB, et al. Effects of delivery room quality improvement on premature infant outcomes. J Perinatol 2017;37:349–54.
[75] Kaempf J, Morris M, Steffen E, Wang L, Dunn M. Continued improvement in morbidity reduction in extremely premature infants. Arch Dis Child Fetal Neonatal 2020:F2–6.
[76] Kaempf JW, Morris M, Austin J, Steffen E, Wang L, Dunn M. Sustained quality improvement collaboration and composite morbidity reduction in extremely low gestational age newborns. Acta Paediatr 2019;108:2199–207.
[77] Goodman D, Ogrinc G, Davies L, Baker GR, Barnsteiner J, Foster TC, et al. Explanation and elaboration of the squire (standards for quality improvement reporting excellence) guidelines, v.2.0: examples of squire elements in the healthcare improvement literature. BMJ Qual Saf 2016;25:e7.
[78] Langley GJ, Moen RD, Nolan KM, Nolan TW, Norman CL, Provost LP. The improvement guide. second ed. San Francisco: Jossey-Bass; 2009.
[79] Institute for Healthcare Improvement. Iihi's collaborative model for achieving breakthrough improvement. IHI innovation series white paper. Cambridge, MA: Institute for Healthcare Improvement; 2003.
[80] Kaempf J, Morris M, Steffen E, Wang L, Dunn M. Continued improvement in morbidity reduction in extremely premature infants. Arch Dis Child Fetal Neonatal; 2020.
[81] Vliegenthart RJS, Onland W, van Wassenaer-Leemhuis AG, De Jaegere APM, Aarnoudse-Moens CSH, van Kaam AH. Restricted ventilation associated with reduced neurodevelopmental impairment in preterm infants. Neonatology 2017; 112:172–9.
[82] Vliegenthart RJS, van Kaam AH, Aarnoudse-Moens CSH, van Wassenaer AG, Onland W. Duration of mechanical ventilation and neurodevelopment in preterm infants. Arch Dis Child Fetal Neonatal Ed 2019;104:F631–5.
[83] Janssen LC, Van Der Spil J, van Kaam AH, Dieleman JP, Andriessen P, Onland W, et al. Minimally invasive surfactant therapy failure: risk factors and outcome. Arch Dis Child Fetal Neonatal Ed 2019;104:F636–42.
[84] Hentschel R, Bohlin K, van Kaam A, Fuchs H, Danhaive O. Surfactant replacement therapy: from biological basis to current clinical practice. Pediatr Res 2020;88: 176–83.
[85] Herting E, Hartel C, Gopel W. Less invasive surfactant administration: best practices and unanswered questions. Curr Opin Pediatr 2020;32:228–34.
[86] Beltempo M, Isayama T, Vento M, Lui K, Kusuda S, Lehtonen L, et al. Respiratory management of extremely preterm infants: an international survey. Neonatology 2018;114:28–36.
[87] van Kaam A, Onland W. Prophylactic low-dose hydrocortisone treatment increases the rate of survival without bronchopulmonary dysplasia in extremely preterm infants. Evid Base Med 2016;21:177.
[88] Wells S, Tamir O, Gray J, Naidoo D, Bekhit M, Goldmann D. Are quality improvement collaboratives effective? A systematic review. BMJ Qual Saf 2018;27: 226–40.
[89] Gupta M, Donovan EF, Henderson Z. State-based perinatal quality collaboratives: pursuing improvements in perinatal health outcomes for all mothers and newborns. Semin Perinatol 2017;41:195–203.
[90] Pai VV, Lee HC, Profit J. Improving uptake of key perinatal interventions using statewide quality collaboratives. Clin Perinatol 2018;45:165–80.
[91] Tumin D, Akpan US, Kohler JA, Uffman JC. Publication bias among conference abstracts reporting on pediatric quality improvement projects. Am J Med Qual 2020;35:274–80.