Powered Air-Purifying Respirator (PAPR) and High-Efficiency Particulate Air (HEPA) Buggies to Improve COVID-19 Safety for the Youngest Children: Evaluation of Prototypes

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Research Article

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Abstract

Introduction:

Young children are susceptible to COVID-19 infection in high-risk settings because they cannot begin vaccination until at least 6 months old and cannot mask safely until at least 2 years old. During essential activities, parents have attempted to protect children in strollers using rain covers, but these provide limited protection against airborne transmission. The investigator examined various models of rain-covered strollers that used either PAPR or HEPA air cleaning devices to provide safer air, so-called “PAPR buggies” and “HEPA buggies.”

Materials and Method

The investigation examined six models that varied based on the type of air filter, (PAPR, small/large HEPA), stroller, and rain cover, and the number of children (single or twin). Key outcomes were a qualitative assessment of strengths and limitations, air flow metrics, and sound intensity. Although all models used safe commercially-sold rain covers, the smallest model was also tested for air quality.

Results

The investigator evaluated each model as acceptable. The PAPR buggies are discrete, whereas the HEPA buggies offer greater flexibility in price and air flow rates. Models had a median of 185.26 air changes per hour, ACH (range of 57.22-951.33), equivalent to 12.35 times the standard for U.S. operating rooms (range of 3.81–63.42). Sound intensity was equivalent to a conversation or office setting (55.5–64.6 dB). Air quality testing revealed no safety concerns. Costs are reasonable for many families.

Discussion

PAPR and HEPA buggies are additional tools families can use as a part of a multifaceted strategy to improve safety in high-risk settings during the COVID-19 pandemic. The models evaluated were reasonable, provided excellent air flow, and had tolerable sound levels. There were no safety concerns, though parents are cautioned to only use commercially-sold, safe rain covers. The investigator offers suggestions for disseminating the widespread use of PAPR and HEPA buggies.

Introduction

Although COVID-19 has been among the top 5 leading causes of death in children under 5 years of age throughout the pandemic [1], parents have had limited options for protecting young children against infection from COVID-19. Children under 5 years old have been among the last to become eligible for vaccines against COVID-19, still ineligible in many nations [2-4]. Children under 6 months of age remain ineligible for vaccines, and account for approximately half of COVID-19 hospitalizations among those under 5 years old [1]. Although vaccines diminish risk of hospitalization and death, their efficacy against infection is more limited over the longer term, particularly as new subvariants emerge [5-7]. Moreover, the long-term sequalae of post-acute COVID-19 or “long COVID,” particularly in response to cumulative reinfections, are emerging, uncertain, and potentially disabling, especially given immune escape [7-11]. Precaution remains warranted, especially in high-risk settings and during surges [12]. Unfortunately, children under 2 years old cannot mask safely [13, 14]. Families can protect young children through isolation, but children need to attend medical wellness visits and other essential care. Single parents and working-class families also have reduced flexibility to keep children home while completing errands. Parents have attempted no shortage of creative solutions, with many covering car seats and strollers (also called “buggies,” “prams,” and “pushchairs”) with commercially-sold rain covers to function like makeshift masks in crowded public indoors areas. These rain covers provide droplet protection but during prolonged outings may be less effective at mitigating aerosol transmission, the primary route by which the virus spreads [15-22]. Thus, children under 2 years of age, and especially younger than 6 months old, have limited protection against a novel virus with uncertain and potentially serious long-term consequences from cumulative lifetime infections. Building on the simple idea of using strollers with rain covers to protect young children, the investigator evaluated several prototypes for pumping filtered clean air into these units, using either Powered Air-Purifying Respirator (PAPR) devices or High-Efficiency Particulate Air (HEPA) filters.

First, consider PAPR devices [23-26], which could be used to pump clean air into a rain-covered stroller, a so-called PAPR buggy (see Figure 1). Traditionally, PAPR equipment sucks ambient air through a high-efficiency particulate filter (e.g., a P100 filter, a stronger level filtration than that of the well-known N95 masks), and pushes the filtered air through a tube into fully-covered headgear. PAPR devices can hold a charge for an extended time (e.g., 4-8 hours) so are highly portable. They provide high-level protection against COVID-19 transmission [23-25]. The main downside is that PAPR equipment is cost prohibitive for most consumers, with full kits typically in the range of $500 to $3,000 USD. A few options for children and babies are available, but these are also cost prohibitive for many families at $400-550. Moreover, strapping a PAPR device around a baby or toddler's waist is impractical, and families may not want the unwanted attention from having a young child in full PAPR headgear. Since many families have already used strollers with rain covers to try to protect children, the investigator examined whether a subset of PAPR equipment could be combined with covered strollers to yield a prototype of a PAPR buggy as a reasonable low-cost option to help protect young children.

Building on the idea of a PAPR buggy, also consider the potential for a HEPA filter [27-32] to provide clean air within a so-called HEPA buggy. The PAPR buggy functions as a larger version of traditional PAPR head gear – it expands upon the traditional space. The HEPA buggy tackles the problem from the opposite direction of shrinking its traditional space. Namely, HEPA filters are used to clean the air in rooms, and a rain-covered stroller could be thought of as an exceptionally small room. All else equal, air filters clean air faster the smaller the room, so putting a HEPA filter within a very small stroller-sized "room" could clean the air rather quickly, even using low-cost HEPA filters.

This prototype evaluation examined the viability of six PAPR and HEPA buggies. The central outcomes were qualitative strengths and limitations, the estimated air cleaning rate, the sound intensity, and safety. The investigator focused on evaluating models relevant to his twin newborns as well as the needs of other families with young children. As one additional tool in a multifaceted mitigation strategy, these examples may help families to identify solutions that can help them to protect their young children during essential activities.

Materials And Methods

Overview

The investigation involved evaluating six prototypes of PAPR and HEPA buggies. The prototypes ranged from including 1–2 children, using PAPR devices or two different sized HEPA filters, and different types of strollers and rain covers. The goal was to showcase different combinations that may be of interest to families. The investigator aimed to summarize strengths and weaknesses, air flow metrics, sound intensity, and safety.

Buggy Models

The investigation reports on six models of PAPR and HEPA buggies (Fig. 2). The PAPR buggies included the twin car seat buggy (Model 1), a similar version for a single child in a rain-covered car seat stroller (Model 2), a single-child rain-covered baby bassinet stroller (Model 3), and a single-toddler upright seated rain-covered stroller (Model 4). The HEPA versions used a small HEPA filter to provide clean air to two babies in car seats covered by a giant rain cover (Model 5), or one large HEPA filter for one child (Model 6), thus, covering a range of tradeoffs.

Each buggy is assembled with three main supplies as depicted in Fig. 2. These include a stroller, a seat (either built into the stroller, a detachable car seat, or a detachable infant bassinet), and an air cleaner (PAPR or HEPA). The PAPR device was a Trudsafe Powered Air Pump for Respirator. The HEPA filters tested were a small RENPHO RP-AP068W and a large AirTheReal AGH 550. The PAPR is self-powered after charged, and the HEPA filters require a portable power station. All supplies are noted in Table 1. Although the air filters are somewhat hidden within the buggies, the final pane of Fig. 2 shows a closer view of each item. Note that consumers have many alternatives for strollers, car seats, bassinets, rain covers, PAPR, HEPA, and power stations. The investigator encourages future researchers and parents to use supplies on hand and engage in pragmatic replications (also called, "extensions," "conceptual replications" or "constructive replications"), rather than a direct replication using the identical but arbitrary parts in Table 1.

Table 1
Guide to Products and Parts for PAPR and HEPA Buggies

Testing Equipment
CADR • Testo 405i hot-wire anemometer ($106), https://www.amazon.com/gp/product/B018VO5GI2/ Sound Intensity, Decibel Meter • RisePRO decibel meter ($20), https://www.amazon.com/gp/product/B01EZZ8B5Q Air Quality, CO2 Monitor • Aranet4 ($249), https://www.amazon.com/gp/product/B07YY7BH2W
Model 1
Stroller • Joovi Twin Roo + frame ($30 used on Craigslist) • Chicco KeyFit 30 car sears ($179 each), https://www.amazon.com/Rear-Facing-Infants-Compatible-Chicco-Strollers/dp/B07MLW6ZSQ/ Rain Cover • Sasha rain and wind cover ($33 each), https://www.amazon.com/gp/product/B07C9JQ5P8/ PAPR with filters • Trudsafe Powered Air Pump for Respirator ($110 each), https://www.amazon.com/gp/product/B09NNKHGT7 • User can purchase non-Trudsafe name-brand 3M filters ($26 for 2 filters), https://www.amazon.com/gp/product/B009POHLRC • If using 3M filters, 3M 701 Black/Orange Filter Adapters ($23 for 2 adapters) are needed, which are very difficult to set up but viable (consider alternatives), https://www.amazon.com/gp/product/B004RH1RXG
Model 2
Stroller • Chicco KeyFit Liteway Stroller ($30 used on Facebook) • Car seat the same as Model 1 Rain Cover • Same as Model 1 PAPR • Same as Model 1
Model 3
Stroller • UppaBaby Bassinet Stroller (very old model, acquired used) Rain Cover • The investigator does not use this model presently, so parents will need to shop for their own recommendations on bassinet rain covers PAPR • Same as Models 1–2
Model 4

Testing Equipment
Stroller • Chicco Liteway Stroller ($30 on Facebook) Rain Cover • Unknown, unbranded and old PAPR • Same as Models 1–3
Model 5
Stroller • Same as Model 1 Rain Cover • Ezkindheit Double-Stroller Rain Cover ($30), https://www.amazon.com/gp/product/B09CGLL4DR/ HEPA filter • RENPHO RP-AP068W ($55), https://www.amazon.com/gp/product/B07Q3DWSTX Power Supply • There are many portable power stations in the $70–100 range that allow 2 or 3-prong outlets. Due to living in a hurricane zone with a recent prolonged power outage and evacuation, the investigator bought a more powerful version that is beyond what most families would need, the Westinghouse iGen300s ($239), https://www.amazon.com/gp/product/B08DSHCK1C
Model 6
Stroller • Same as Models 1 and 5 Rain Cover • Same as Model 5 HEPA filter • AirTheReal AGH 550 ($220), https://www.projectn95.org/products/hepa-filter-agh550-black-air-purifier Power Supply • Same as Model 5

parents to use supplies on hand and engage in pragmatic replications (also called, “extensions,” “conceptual replications” or “constructive replications”), rather than a direct replication using the identical but arbitrary parts in Table 1.

Supply price estimates are shown in U.S. dollars (USD). Approximate exchange rates are that $100 (USD) = 93.8 € = 82.7 £ = 13,282.8 ¥.

Air Flow

The evaluation assessed three metrics of air flow. The first metric was the clean air delivery rate (CADR) for each device, the rate at which it pumps clean air. The PAPR manufacturer did not supply a CADR estimate, so the investigator measured it using a Testo 405i hot-wire anemometer, achieving values similar to those manufacturers of other PAPRs report. The HEPA manufacturers did provide CADR estimates, which the investigator confirmed via the anemometer.

Second, the investigator estimated the number of air changes per hour (ACH) within the enclosed area of each model, which can be thought of as the speed of cleaning the air within a given sized volume. These estimates required manually measuring the interior dimensions of each model, often irregular, and using trigonometry to estimate area and compute volume. Rounded corners were treated as larger polygons to err toward overestimating volume and, thus, underestimating ACH. ACH was computed using the standard formula [33], noted in Table 2. Many engineers and retailers use the units of “cfm” or ft^3/minute, so statistics include both Imperial and SI units. Table 3 provides a spreadsheet of spatial volume (right column) by CADR (top row) so that parents less familiar with engineering equations can quickly estimate ACH (Imperial and SI units provided). They would just need to calculate the approximate spatial volume (or a stroller enclosure, room, or other place) and get the CADR estimate from the manufacturer.

Third, given that CADR and ACH are unfamiliar acronyms to many parents who may benefit from this article, the investigator also computer a final metric, called “Operating Room

Table 2
Formulas for Converting Air Filter Clean Air Delivery Rate (CADR) to Air Changes Per Hour (ACH) and Operation Room Equivalents (ORE)

ACH in Imperial Units			
CADR of PAPR or HEPA in ft^3/minute (also called “cfm”)	X 60 minutes in an hour	÷ Room or Enclosure Size in ft^3	= ACH
ACH in SI Units			
CADR of PAPR or HEPA in m^3/minute	X 60 minutes in an hour	÷ Room or Enclosure Size in m^3	= ACH
Operating Room Equivalents			
ACH	÷ 15 ACH of an Operating Room	= Operating Room Equivalents	

Table 3
Chart for Converting Air Filter Clean Air Delivery Rate (CADR) and Room (or Rain Cover Enclosure) Size into Air Changes Per Hour (ACH), using SI or Imperial Units

SI Units														
	CADR of PAPR or HEPA Air Filter (m^3/minute)													
Room or Buggy Size (m^3)	0.1	0.25	0.5	0.75	1	2	3	4	5	10	15	20	25	30
0.03	200	500	1000	1500	2000	4000	6000	8000	10000	20000	30000	40000	50000	60000
0.06	100	250	500	750	1000	2000	3000	4000	5000	10000	15000	20000	25000	30000
0.09	67	167	333	500	667	1333	2000	2667	3333	6667	10000	13333	16667	20000
0.12	50	125	250	375	500	1000	1500	2000	2500	5000	7500	10000	12500	15000
0.15	40	100	200	300	400	800	1200	1600	2000	4000	6000	8000	10000	12000
0.18	33	83	167	250	333	667	1000	1333	1667	3333	5000	6667	8333	10000
0.21	29	71	143	214	286	571	857	1143	1429	2857	4286	5714	7143	8571
0.24	25	63	125	188	250	500	750	1000	1250	2500	3750	5000	6250	7500
0.27	22	56	111	167	222	444	667	889	1111	2222	3333	4444	5556	6667
0.30	20	50	100	150	200	400	600	800	1000	2000	3000	4000	5000	6000
0.33	18	45	91	136	182	364	545	727	909	1818	2727	3636	4545	5455
0.36	17	42	83	125	167	333	500	667	833	1667	2500	3333	4167	5000
0.39	15	38	77	115	154	308	462	615	769	1538	2308	3077	3846	4615
0.42	14	36	71	107	143	286	429	571	714	1429	2143	2857	3571	4286
0.45	13	33	67	100	133	267	400	533	667	1333	2000	2667	3333	4000
0.48	13	31	63	94	125	250	375	500	625	1250	1875	2500	3125	3750
0.51	12	29	59	88	118	235	353	471	588	1176	1765	2353	2941	3529
0.54	11	28	56	83	111	222	333	444	556	1111	1667	2222	2778	3333
0.57	11	26	53	79	105	211	316	421	526	1053	1579	2105	2632	3158
0.60	10	25	50	75	100	200	300	400	500	1000	1500	2000	2500	3000
0.63	10	24	48	71	95	190	286	381	476	952	1429	1905	2381	2857
0.66	9	23	45	68	91	182	273	364	455	909	1364	1818	2273	2727
0.69	9	22	43	65	87	174	261	348	435	870	1304	1739	2174	2609
0.72	8	21	42	63	83	167	250	333	417	833	1250	1667	2083	2500
0.75	8	20	40	60	80	160	240	320	400	800	1200	1600	2000	2400
0.78	8	19	38	58	77	154	231	308	385	769	1154	1538	1923	2308
0.81	7	19	37	56	74	148	222	296	370	741	1111	1481	1852	2222
0.84	7	18	36	54	71	143	214	286	357	714	1071	1429	1786	2143
0.87	7	17	34	52	69	138	207	276	345	690	1034	1379	1724	2069
0.90	7	17	33	50	67	133	200	267	333	667	1000	1333	1667	2000

SI Units														
1.00	6	15	30	45	60	120	180	240	300	600	900	1200	1500	1800
2.00	3	8	15	23	30	60	90	120	150	300	450	600	750	900
3.00	2	5	10	15	20	40	60	80	100	200	300	400	500	600
4.00	2	4	8	11	15	30	45	60	75	150	225	300	375	450
5.00	1	3	6	9	12	24	36	48	60	120	180	240	300	360
6.00	1	3	5	8	10	20	30	40	50	100	150	200	250	300
7.00	1	2	4	6	9	17	26	34	43	86	129	171	214	257
8.00	1	2	4	6	8	15	23	30	38	75	113	150	188	225
9.00	1	2	3	5	7	13	20	27	33	67	100	133	167	200
10.00	1	2	3	5	6	12	18	24	30	60	90	120	150	180
20.00	0	1	2	2	3	6	9	12	15	30	45	60	75	90
30.00	0	1	1	2	2	4	6	8	10	20	30	40	50	60
40.00	0	0	1	1	2	3	5	6	8	15	23	30	38	45
50.00	0	0	1	1	1	2	4	5	6	12	18	24	30	36
100.00	0	0	0	0	1	1	2	2	3	6	9	12	15	18
Imperial Units														
	CADR of PAPR or HEPA Air Filter (ft^3/minute)													
Room or Buggy Size (ft^3)	5	10	25	50	75	100	150	200	250	300	400	500	750	1000
1	300	600	1500	3000	4500	6000	9000	12000	15000	18000	24000	30000	45000	60000
2	150	300	750	1500	2250	3000	4500	6000	7500	9000	12000	15000	22500	30000
3	100	200	500	1000	1500	2000	3000	4000	5000	6000	8000	10000	15000	20000
4	75	150	375	750	1125	1500	2250	3000	3750	4500	6000	7500	11250	15000
5	60	120	300	600	900	1200	1800	2400	3000	3600	4800	6000	9000	12000
6	50	100	250	500	750	1000	1500	2000	2500	3000	4000	5000	7500	10000
7	43	86	214	429	643	857	1286	1714	2143	2571	3429	4286	6429	8571
8	38	75	188	375	563	750	1125	1500	1875	2250	3000	3750	5625	7500
9	33	67	167	333	500	667	1000	1333	1667	2000	2667	3333	5000	6667
10	30	60	150	300	450	600	900	1200	1500	1800	2400	3000	4500	6000
11	27	55	136	273	409	545	818	1091	1364	1636	2182	2727	4091	5455
12	25	50	125	250	375	500	750	1000	1250	1500	2000	2500	3750	5000
13	23	46	115	231	346	462	692	923	1154	1385	1846	2308	3462	4615
14	21	43	107	214	321	429	643	857	1071	1286	1714	2143	3214	4286
15	20	40	100	200	300	400	600	800	1000	1200	1600	2000	3000	4000
16	19	38	94	188	281	375	563	750	938	1125	1500	1875	2813	3750

SI Units														
17	18	35	88	176	265	353	529	706	882	1059	1412	1765	2647	3529
18	17	33	83	167	250	333	500	667	833	1000	1333	1667	2500	3333
19	16	32	79	158	237	316	474	632	789	947	1263	1579	2368	3158
20	15	30	75	150	225	300	450	600	750	900	1200	1500	2250	3000
21	14	29	71	143	214	286	429	571	714	857	1143	1429	2143	2857
22	14	27	68	136	205	273	409	545	682	818	1091	1364	2045	2727
23	13	26	65	130	196	261	391	522	652	783	1043	1304	1957	2609
24	13	25	63	125	188	250	375	500	625	750	1000	1250	1875	2500
25	12	24	60	120	180	240	360	480	600	720	960	1200	1800	2400
26	12	23	58	115	173	231	346	462	577	692	923	1154	1731	2308
27	11	22	56	111	167	222	333	444	556	667	889	1111	1667	2222
28	11	21	54	107	161	214	321	429	536	643	857	1071	1607	2143
29	10	21	52	103	155	207	310	414	517	621	828	1034	1552	2069
30	10	20	50	100	150	200	300	400	500	600	800	1000	1500	2000
40	8	15	38	75	113	150	225	300	375	450	600	750	1125	1500
50	6	12	30	60	90	120	180	240	300	360	480	600	900	1200
60	5	10	25	50	75	100	150	200	250	300	400	500	750	1000
70	4	9	21	43	64	86	129	171	214	257	343	429	643	857
80	4	8	19	38	56	75	113	150	188	225	300	375	563	750
90	3	7	17	33	50	67	100	133	167	200	267	333	500	667
100	3	6	15	30	45	60	90	120	150	180	240	300	450	600
200	2	3	8	15	23	30	45	60	75	90	120	150	225	300
300	1	2	5	10	15	20	30	40	50	60	80	100	150	200
400	1	2	4	8	11	15	23	30	38	45	60	75	113	150
500	1	1	3	6	9	12	18	24	30	36	48	60	90	120
600	1	1	3	5	8	10	15	20	25	30	40	50	75	100
700	0	1	2	4	6	9	13	17	21	26	34	43	64	86
800	0	1	2	4	6	8	11	15	19	23	30	38	56	75
900	0	1	2	3	5	7	10	13	17	20	27	33	50	67
1,000	0	1	2	3	5	6	9	12	15	18	24	30	45	60
2,000	0	0	1	2	2	3	5	6	8	9	12	15	23	30
3,000	0	0	1	1	2	2	3	4	5	6	8	10	15	20
4,000	0	0	0	1	1	2	2	3	4	5	6	8	11	15
5,000	0	0	0	1	1	1	2	2	3	4	5	6	9	12
6,000	0	0	0	1	1	1	2	2	3	3	4	5	8	10
7,000	0	0	0	0	1	1	1	2	2	3	3	4	6	9
8,000	0	0	0	0	1	1	1	2	2	2	3	4	6	8

SI Units														
9,000	0	0	0	0	1	1	1	1	2	2	3	3	5	7
10,000	0	0	0	0	0	1	1	1	2	2	2	3	5	6

Note. The sizes in the left column can be used for the interior enclosures of buggies or room sizes. Calculate the volume of rectangular prisms like rooms as the product of the dimensions (i.e., length X width X height), or use trigonometry to calculate the area of other polygons (e.g., side of an enclosed stroller) and multiply it by the remaining dimension. Contact the corresponding author for any help. The CADR values can be used for PAPR devices or HEPA filters. If buying a HEPA filter, the manufacturer may provide the CADR usually listed in cfm (cubic feet per minute) units, but note that this reflects the highest and loudest setting. HEPA filters often need to be set to one setting lower for tolerable volume, so a useful practice may be to buy HEPA filters with an advertised CADR 150% of the level desired. The ACH estimates in this table can be converted to “Operating Room Equivalents” by dividing by 15.

Equivalents.” The U.S. Centers for Disease Control and Prevention (CDC) stipulates that operating rooms should maintain at least 15 ACH [34]. Thus, the investigator also divided ACH by 15 to yield Operating Room Equivalents (see Table 2). For example, an ACH of 45 would indicate 3 Operating Room Equivalents or cleaning the air at 3 times the CDC operating room standard.

Sound Intensity

A RisePRO decibel meter was used to estimate sound intensity for each model. Average measurements were recorded from 1.83 m (6 ft) away within a quiet room, subtracting ambient sound intensity using a standard log scale decibel calculator.

Safety

Although commercially-sold stroller rain covers have vents to prevent the build-up of poor air quality or asphyxiation, cautious readers may appreciate being able to cite additional testing. Asphyxiation risk would be higher the smaller the enclosed volume, so the investigator evaluated Model 2 for CO_2 buildup during use via an Aranet4 CO_2 monitor. The investigator recorded ambient CO_2 levels, CO_2 levels in the uncovered car seat with baby present, and CO_2 levels in the covered car seat with baby present and PAPR running, reporting average values once CO_2 levels stabilized (plateaued) under each situation. Recordings within the car seat were 12 inches away from a 2-month-old’s mouth. Reference levels are also reported.

Results

Description and Qualitative Appraisal of PAPR Buggies

Models 1–4 involved a PAPR air pump with P100 filters and tube pumping clean air into rain-covered strollers (Figs. 1 and 2). The PAPR pump and filters sit in the stroller undercarriage. The PAPR system charges in advance and holds power for approximately 4 hours, per the manufacturer. Covering the non-filter portions of the air pump with a light muslin blanket keeps system discrete from observers. The air supply tube ascends discretely up the stroller frame and into the covered car seat, supplying clean air. The plastic rain cover has vents throughout to meet safety standards, and these act as exhaust pathways when the PAPR is connected. Note that the tube enters the car seat from behind the head. This allows clean air to enter near the head and push old air out toward the feet. Having the tube ascend from the front could irritate children’s eyes, or allow them to drop toys or food into the tube. Afterall, parents do many “strange” things to protect their children. The PAPR model could be used with twin car seats (Model 1), an individual car seat stroller (Model 2), a baby bassinet stroller (Model 3), or an upright toddler seated stroller (Model 4).

The PAPR buggy has several key strengths. PAPR devices are self-charged, so there is no need for an additional power supply. The system is visually discrete and quiet based on the investigator’s use of Model 1 during child wellness visits. The whole system goes unnoticed in a large waiting room; however, the sound is obvious within a small clinical encounter room. Over a dozen clinicians caring for the investigators’ children have observed Model 1; none voiced criticism, and several were intrigued. The cost is reasonable. Setup is simple. The system would work well with car seat strollers, bassinet strollers, or standard seated strollers.

The PAPR buggy has limitations too. PAPR equipment does not include a meter indicating when filters should be replaced, so users will need to estimate or track hours of use manually. If parents want to use pump filters from a more well-known brand like 3M, this requires adapters, which work but were difficult to connect. PAPR equipment could look suspicious to the uninformed, like a gaseous weapon (see Fig. 2, Supplies).

Description And Qualitative Appraisal Of Hepa Buggies

Models 5 and 6 involved using HEPA filters underneath large rain-covered strollers (Fig. 2). The HEPA filter is powered by a portable power station, cleans the air, and blows it into the rain-covered stroller. The large rain covers have vents and open to the bottom of the stroller to allow stale air to leave. In the twin car seat version (Model 5), a HEPA filter was selected that specifically fit in the mid-section of the undercarriage to push filtered air up through the center. Alternatively, as in Model 6 (Fig. 2), one could acquire a twin stroller and use the extra room to store a bulky, powerful HEPA filter in one half and a child in the other. As noted in the parts list (Table 1), the twin stroller frame was only $30 used. Others may prefer to attach a HEPA filter to a toddler “stroller board” that clips on to the back of a single-child stroller. It may be helpful to use bungie cords to secure the HEPA filter. Given the variety of HEPA filters and stroller setups, there is plenty of room for testing other designs.

Power is a key design strength. Even a small HEPA filter can provide considerable air filtration for a “room” as small as a stroller (see Table 3 and next section of the Results). Moreover, a large HEPA filter would have the added benefit that it could be removed from a stroller and used to clean the air of a patient encounter room during medical visits. For example, as noted in Table 3, a HEPA filter with a CADR of 5.66 m^3/minute (200 ft^3/minute) could clean a typical patient encounter room (3.05 m x 3.05 m x 2.44 m = 22.70 m^3; 10 ft x 10 ft x 8 ft = 800 ft^3) at 15 ACH, equivalent to operating room standards.

The design has several practical limitations, mainly portability and acceptability. HEPA filters are often bulky, non-discrete, and require an external power station. They need to be held securely to avoid tipping over, which can lead them to shut off, blow air in an unhelpful direction, or get damaged. Consumers will need to attend to product dimensions in advance to ensure that a particular HEPA filter will fit well with a given stroller and cover. Thus, they are more work to set up than PAPR buggies.

Air Cleaning, Sound Intensity, And Safety Of Papr And Hepa Buggies

Table 4 summarizes the air cleaning rates and sound intensity for each of the 6 models. The models were designed for 1 or 2 young children and used 1–2 PAPR devices, a small HEPA filter, or large HEPA filter. The rain covers enclosed interior volumes ranging from 0.05 m^3 to 0.54 m^3 (1.75 to 19.11 ft^3). The PAPR provided a CADR of 0.16 m^3/minute (5.77 ft^3/minute), whereas the HEPA filters provided 1.56 m^3/minute and 8.58 m^3/minute (55 ft^3/minute and 303 ft^3/minute), respectively, suitable for the larger enclosures. The models provided a median of 185.26 ACH. Note that models 1 and 2 (PAPR) provided similar air cleaning as model

Table 4
Air Cleaning Rates and Sound Intensity for Prototypical Models of PAPR and HEPA Buggies

Model	Stroller	Children	Filtration Type	Interior Size	Clean Air Delivery Rate (CADR)	Air Changes Per Hour (ACH)	Operating Room Equivalents	Sound Intensity
1	Twin car seat baby stroller	2	2 PAPRs	0.05 m^3 (1.75 ft^3)	0.16 m^3/min (5.77 ft^3/min)	197.83	13.19	60.6 dB
2	Car seat baby stroller	1	PAPR	0.05 m^3 (1.75 ft^3)	0.16 m^3/min (5.77 ft^3/min)	197.83	13.19	57.8 dB
3	Bassinet baby stroller	1	PAPR	0.17 m^3 (6.05 ft^3)	0.16 m^3/min (5.77 ft^3/min)	57.22	3.81	57.8 dB
4	Upright toddler seat stroller	1	PAPR	0.08 m^3 (2.84 ft^3)	0.16 m^3/min (5.77 ft^3/min)	121.90	8.13	57.8 dB
5	Twin car seat baby stroller	2	Small HEPA	0.54 m^3 (19.11 ft^3)	1.56 m^3/min (55.00 ft^3/min)	172.68	11.51	55.5 dB
6	Twin car seat baby stroller	1	Large HEPA	0.54 m^3 (19.11 ft^3)	8.58 m^3/min (303.00 ft^3/min)	951.33	63.42	64.6 dB

Note. PAPR = Powered Air-Purifying Respirator, HEPA = High-Efficiency Particulate Air filer. In Model 1, the sizing and air filtration rates are for each of two separately-enclosed car seat units, whereas in Model 5 the car seats are enclosed within a single large rain cover. Operating rooms are recommended by the Centers for Disease Control and Prevention (CDC) to have a minimum of 15 ACH, so “Operation Room Equivalents” reflect the ACH divided by 15. Sound intensity ratings subtract ambient intensity using a standard log-based decibel calculator.

5 (small HEPA). In terms more relatable to non-engineers, the models provided a median air cleaning rate the equivalent of 12.35 times that of an operating room.

The sound intensity was also similar across models, ranging from 55.5 to 64.6 dB. These values are similar to a normal conversation or office noise.

The investigator also safety tested the smallest model (Model 2). As expected for a commercially-sold stroller rain cover, CO_2 levels plateaued at ordinary, safe levels, similar to what is commonly observed in indoor settings, likes homes and businesses (Table 5).

Discussion

This investigation examined six models of PAPR and HEPA buggies and determined they provide reasonable options as a part of a multifaceted strategy for promoting the safety of the youngest children during the COVID-19 pandemic. The buggies provided good airflow, ranging from 57 to 951 ACH, equivalent to 3.8 to 63.4 times the air cleaning rate of a U.S. operating room [34]. The air cleaning rates were dramatic, and PAPR and HEPA buggies should be a public health priority. All models had sound intensity similar to the volume of normal conversation or an office, indicating good usability. Moreover, the buggies are practical and economical for many families.

They mostly require supplies families already have on hand, such as car seats, strollers, and rain covers. The additional costs of a PAPR device ($110) or small HEPA filters ($55) can fit within many families' budgets (see Table 1). Implications for family use, future prototype investigations, and widespread dissemination are discussed.

Parents can choose among the PAPR and HEPA buggies tested or explore new models to meet families' needs. The simplest option is to buy the PAPR device the investigator tested and install it on one's rain-covered stroller. However, other options are worth considering. For one, low-cost PAPR devices may not always be available if in high demand or if suppliers hit COVID-19-related manufacturing issues. HEPA options provide greater flexibility and are produced widely, which provides a useful backup against PAPR solutions. Small low-cost HEPA filters can provide excellent within-buggy air filtration. Larger options can also clean the air of

Table 5
CO_2 Measurements to Validate Safety of Commercial Stroller Rain Cover for Smallest Model (Model 2)

Context	CO_2 Level
Buggy Testing	
Ambient levels in investigator's home	576 ppm
Inside uncovered car seat, occupied by 2-month-old boy, CO_2 monitor 12 inches from mouth	681 ppm
Inside car seat enclosed by rain cover occupied by 2-month-old boy, CO_2 monitor 12 inches from mouth	977 ppm
Reference Levels	
Outdoors	400–450 ppm
Common ambient CO_2 levels in homes and businesses	550-1,400 ppm
Inside cars	550-4,000 ppm
Poor levels of ventilation that may cause headaches, sleepiness, or perceptions of stale air	2,000–5,000 ppm
Occupational Safety and Health Administration (OSHA) warning level for risk of asphyxiation during 8-hour continuous exposure	5,000 ppm

Note. CO_2 levels were averages after reaching plateaus.

clinical encounter rooms when desired. Nonetheless, even the lowest cost options are a financial struggle for some families that would appreciate HEPA buggies, indicating the need for community-based, federal, and international programs to make air cleaners more available.

Despite their strengths, PAPR and HEPA buggies are not a panacea for the pandemic but rather a part of a broader strategy of multifaceted mitigation [15–22, 32, 35, 36]. No mitigation measure provides 100% protection, which is why multilayered mitigation is important, including use of vaccines, masking, reduced social contact, physical distancing, ventilation, filtration, remote interactions, serial and symptomatic testing, and early treatment, to the extent possible. As well, these buggies only offer young children any potential benefit while actually inside them, not when children must necessarily venture out for medical procedures, including the most basic of being weighed, measured, and physically examined for well visits. The investigator remains astounded that 3 years into the COVID-19 pandemic, no scientist has found a safe way for the youngest children to mask. The investigator has attempted methods of attaching PAPR devices to nebulizer mouth pieces to provide mask-like support without the asphyxiation risk faced by young maskers, but they remain impractical. Similarly, oxygen tanks with nasal cannula lines remain cost prohibitive and unwieldy. An important future direction is for more scientists to evaluate prototypes of methods for keeping young children safer from airborne viral transmission during essential activities.

As a key reminder, parents are encouraged to put standard pre-pandemic safety precautions first when using PAPR and HEPA buggies. Foremost, parents should only use commercially-sold rain covers that include outgoing air vents. The present investigation found that such covers keep CO_2 levels within the normal range of everyday homes and businesses and do not impose an asphyxiation risk. Undoubtedly, many families already have rain covers on hand that have repeatedly proven safe and can be used as a part of PAPR and HEPA buggy systems. Intermediary non-profits that vet public health products, such as Project N95 [37], should consider independently testing and selling key supplies listed in Table 1. Parents should never craft their own covers, especially out of unventilated materials like garbage bags or tarps that could harm children. CO_2 monitors should be used to evaluate safety when in question, and the investigator accepts no liability for misuse. Second, filters of PAPR filters should always remain uncovered, and users should follow manufacturer instructions. Third, HEPA filters should be securely fastened to strollers and allow unblocked airflow according to manufacturer instructions. Forth, children should never be left unattended in such systems in case PAPR devices or HEPA power supplies run out of energy or malfunction. Although the above indications are common sense, their gravity warrants stating them.

Parents can normalize and help other families learn about PAPR and HEPA buggies by sharing on social media. The investigator recommends tagging pictures, descriptions, instructions, this article, and follow-up studies using hashtags such as #PAPRbuggy and #HEPAbuggy. A similar initiative has effectively disseminated information to improve indoor air quality in schools and homes using do-it-yourself (DIY) air cleaners called Corsi-Rosenthal Boxes [33, 38–40], using the #CorsiRosenthalBox hashtag. Nonetheless, psychology research on "behavioral inoculation" [41–43] indicates that parents should be forewarned of the risks of disseminating on social media in order to reduce the sting of trolling. As summarized in the Table 6, trolls may use several common and simplistic themes to attack parents who aim to protect children, mocking their mental health, calling them child abusers, or minimizing the pandemic. The investigator expects to see crude comments on these buggies, such as "bubble boy" or Nazi-rhetoric like "gas chamber." Such comments are expected and should be tallied by parents as a badge of honor in the battle for public health. Social media platforms are more likely to display content with high engagement metrics, so trolling remarks are actually instrumental in ensuring such posts gain broader dissemination.

Conclusions

PAPR and HEPA buggies provide 3.8–63.4 times the clean airflow of operating rooms, which can help unmaskable young children during essential activities of the ongoing airborne

Table 6
Common Themes Used to Troll Parents Protecting Children from COVID-19, Listed for the Purposes of "Behavioral Inoculation," or Reducing the Sting if Parents Later Hear these Messages

• Mental health: Saying parents are "insane," "lunatics," "mentally ill," "living in fear," "fearmongers," "paranoid," "hypochondriacs," "unhealthy," "overreacting," "brainwashed," needing to "seek help," "sheep," or victims who "drank the Kool-Aid"
• Anti-parent: "Child abuser," "it's bad for kids' mental health," "ruining your kids"
• Generic demeaning remarks: "weak," "unfit," stupid," "pathetic," "not cool," "whiner"
• Denying risks toward children: "Children are low risk," "kids need to get exposed to things"
• General denial of severity: "it's just like the flu," "it's just a cold," "it's mild," "it's endemic," "it will be endemic soon," "long COVID is just anxiety," suggesting infections or reinfects are a "good thing," "I've had COVID twice, and it's nothing to be afraid of," "even Europeans don't mask anymore"
• You only live once (YOLO): "You just need to live," "you can't be a hermit forever," "you can't isolate forever"
• Mislabeling as anti-vaccine: called "anti-vax" for supporting multifaceted mitigation, mocked as vaccine flip-floppers
• Minimizing airborne transmission: "we require vaccines, so everyone is safe," "we have hand sanitizer and do daily deep cleans of all surfaces," "it can't spread beyond 6 feet"
• Fatalism: "infection is inevitable"
• Ostracism: "just stay home"
• Social media mocking: derogatory and ad hominem attacks toward one's page or picture, "pronouns in bio," "masked in profile," clown face emoji, tear laughter emoji
• Likely PAPR/HEPA buggy-specific remarks: "Bubble boy," "bubble girl," any Nazi references, particularly related to "gas chambers"

Note. Thank you to > 100 of the investigator's Twitter followers who contributed to summarizing the various trolling responses they have received as COVID-cautious parents, either online or in person, not specific to PAPR and HEPA buggies.

COVID-19 pandemic. Families can choose among several reasonable and low-cost options for PAPR and HEPA buggies and are encouraged to share photos on social media to increase dissemination. Future directions include developing and testing novel approaches to protecting the youngest children.

Declarations

Ethics approval and consent to participate

Approval: The Tulane University Institutional Review Board (IRB) reviewed and approve the project as non-human subjects research (2023-005). All methods were carried out in accordance with relevant guidelines and regulations.

Consent: Not applicable, per IRB. Stroller dimension and air quality data, not a systematic prospective investigation of human subjects' attributes.

Consent for publication

As the project was conducted in the corresponding author's home, he completed the BMC consent for publication form. No further consent documents were applicable.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Competing interests

The author declares that they have no competing interests.

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Author Contributions

MH was responsible for all aspects of the research process.

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Figures

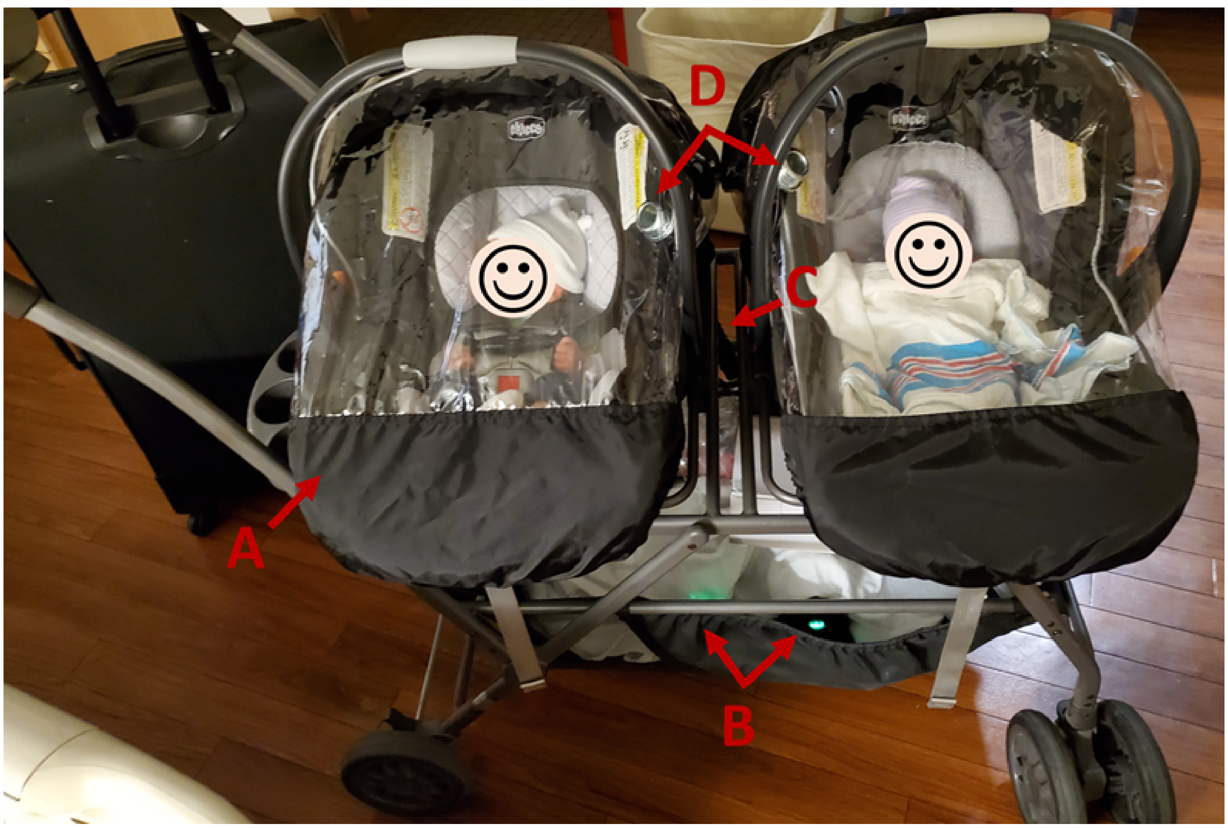

Figure 1

First Test-Run of a PAPR-Buggy to Improve COVID-19 Safety (Model 1 of 6 Tested). In this model, two car seats are covered individually with safe commercially-sold rain covers (A). A PAPR air-cleaning device for each child sits in the stroller's undercarriage (B), with the non-filter portions hidden by a muslin blanket. The black PAPR tubes discretely ascend the stroller frame (C) and tuck into the rain covers (D) to release fresh air. Six models were tested for 1-2 children using various strollers, rain covers, and PAPR/HEPA filters. The investigator's twins tested the models, starting with their first trip home from the hospital, pictured.

multifaceted mitigation strategy, these examples may help families to identify solutions that can help them to protect their young children during essential activities.

Figure 2

Case Prototypes of PAPR Buggies (Top Row) and HEPA Buggies (Bottom). Model 1: Twin children in individual covered car seats, each with separate PAPR devices. Model 2: Single child version for a covered car seat with PAPR device. Model 3: Bassinet stroller with PAPR device, requires cover, not shown. Model 4: Single seated stroller, covered, with PAPR device. Model 5: Two car seats with large cover, using a small HEPA attached to a portable power station. Model 6: Single car seat attached to a twin stroller frame with large cover, using a large HEPA and power station. Supplies shown include small and large HEPA filters, the portable power source, and two PAPR devices, each shown with a manufacturer's P100 filter (brown) and 3M version (pink).