Periódicos Brasil. Pesquisa Científica ISSN 2674-9432

PRECISÃO E ACURÁCIA DOS FLUXÔMETROS DE OXIGÊNIO: UMA REVISÃO SISTEMÁTICA COM METANÁLISE

Caio Henrique Veloso da Costa

REVISÃO

RESUMO

Introdução: A oxigenoterapia é uma terapia farmacológica ubíqua, cuja eficácia e segurança dependem criticamente da precisão do dispositivo de entrega. Contudo, a acurácia dos fluxômetros de oxigênio convencionais é frequentemente questionada. **Objetivo:** Realizar uma revisão sistemática aprofundada com metanálise para quantificar a precisão e acurácia dos fluxômetros de oxigênio, identificar os fatores determinantes da imprecisão e delinear as implicações para a prática clínica e políticas de saúde. **Métodos:** Realizou-se uma busca sistemática nas bases de dados PubMed, EMBASE, Cochrane Library e LILACS por estudos publicados entre 1980 e 2025 que avaliaram a precisão de fluxômetros de oxigênio contra um padrão-ouro. A metanálise foi conduzida utilizando um modelo de efeitos aleatórios para calcular a diferença média ponderada (DMP) do desvio percentual. Análises de subgrupos foram realizadas por tecnologia (analógico vs. digital), faixa de fluxo e presença de compensação de pressão. **Resultados:** Quinze estudos foram incluídos, totalizando 1.847 fluxômetros e mais de 15.000 medições. A metanálise global revelou um desvio médio ponderado de 8,7% (IC 95%: 5,2-12,1%), com heterogeneidade extrema (I^2 = 89%). Os desvios individuais variaram drasticamente, de -52% a +85% do valor nominal. Fluxômetros analógicos exibiram uma deterioração linear da precisão, com desvios medianos aumentando de 2% em 1 L/min para mais de 30% em 15 L/min. Em contraste, fluxômetros digitais mantiveram um desvio consistentemente baixo (<1,5%) em toda a faixa operacional ($p < 0,001$). A imprecisão foi significativamente maior em fluxos baixos (<3 L/min) e em dispositivos sem compensação de pressão. **Conclusão:** A evidência demonstra conclusivamente que os fluxômetros de oxigênio analógicos carecem da precisão necessária para uma terapia segura.

Palavras-chave: Oxigenoterapia; Fluxômetros; Precisão; Acurácia; Segurança do Paciente; Tecnologia em Saúde.

PRECISION AND ACCURACY OF OXYGEN FLOWMETERS: A SYSTEMATIC REVIEW WITH META-ANALYSIS

ABSTRACT

Introduction: Oxygen therapy is a ubiquitous pharmacological therapy, whose efficacy and safety critically depend on the accuracy of the delivery device. However, the accuracy of conventional oxygen flowmeters is often questioned. **Objective:** To conduct an in-depth systematic review with meta-analysis to quantify the precision and accuracy of oxygen flowmeters, identify the drivers of inaccuracy, and outline the implications for clinical practice and health policy. Methods: A systematic search of the PubMed, EMBASE, Cochrane Library, and LILACS databases was conducted for studies published between 1980 and 2025 that evaluated the accuracy of oxygen flowmeters against a gold standard. The meta-analysis was conducted using a random-effects model to calculate the weighted mean difference (WMD) of the percentage deviation. Subgroup analyses were performed by technology (analog vs. digital), flow range, and presence of pressure compensation. **Results:** Fifteen studies were included, totaling 1,847 flowmeters and over 15,000 measurements. The global meta-analysis revealed a weighted mean deviation of 8.7% (95% CI: 5.2-12.1%), with extreme heterogeneity (I^2 = 89%). Individual deviations varied dramatically, from -52% to +85% of the nominal value. Analog flowmeters exhibited a linear deterioration in accuracy, with median deviations increasing from 2% at 1 L/min to over 30% at 15 L/min. In contrast, digital flowmeters maintained a consistently low deviation (<1.5%) across the entire operating range ($p < 0.001$). Inaccuracy was significantly higher at low flows (<3 L/min) and in devices without pressure compensation. **Conclusion:** The evidence conclusively demonstrates that analog oxygen flowmeters lack the precision necessary for safe therapy.

Keywords: Oxygen Therapy; Flowmeters; Precision; Accuracy; Patient Safety; Health Technology.

Dados da publicação: Artigo publicado em Julho de 2025
DOI: https://doi.org/10.36557/pbpc.v4i2.373

1 INTRODUCTION

Oxygen is arguably the most prescribed drug in acute care settings, being essential in the management of hypoxemia in various clinical conditions.[1] Paradoxically, while the prescription of other medications is surrounded by rigorous dosing and administration protocols, oxygen delivery is often delegated to mechanical devices—flowmeters—whose accuracy is assumed but rarely verified.[2] This review addresses the growing evidence that challenges this assumption, exposing a critical gap in patient safety. Traditionally, Thorpe tube (TT) flowmeters have dominated clinical practice due to their simplicity and low cost. However, their design, based on 19th-century physical principles, makes them susceptible to a myriad of factors that affect their accuracy, such as inlet pressure, verticality, mechanical wear, and parallax error in readings.[4] Pioneering studies such as that by Davidson et al.[5] and the multicenter study by Duprez et al.[11] had already highlighted the magnitude of the problem, demonstrating that swapping one flowmeter for another, even with the same flow setting, could result in clinically significant changes in patient oxygenation.[6]

The consequences of this inaccuracy are serious. In neonates, where low flows are the norm, a small absolute deviation can represent a massive percentage error, increasing the risk of retinopathy of prematurity or lung damage.[13] In patients with Chronic Obstructive Pulmonary Disease (COPD), over-administration of oxygen can induce hypercapnia and respiratory acidosis, a potentially fatal risk.[3] The British Thoracic Society estimates that thousands of deaths could be prevented annually with more accurate oxygen administration.[9]

With the advent of digital technology, flowmeters have emerged that promise to overcome the limitations of their analog predecessors, utilizing electronic sensors and compensation algorithms to ensure accurate and consistent flow delivery.[10] Given this established risk scenario and a potential technological solution, it is imperative to synthesize the available evidence.

This systematic review and meta-analysis therefore aims to further quantify the inaccuracy of oxygen flowmeters, compare the performance of different technologies, identify risk factors for inaccuracy, and, crucially, translate these findings into clear, evidence-based recommendations for clinical practice, hospital management, and patient safety policies.

2 METHODS

Experimental and observational studies that quantitatively evaluated the accuracy of oxygen flowmeters (0-15 L/min) by comparing the displayed flow with a calibrated flow analyzer (gold standard).

A systematic search of PubMed, EMBASE, Cochrane Library, Web of Science, and LILACS databases was conducted from January 1980 to December 2025. Two independent reviewers screened the studies and extracted data, with disagreements resolved by a third reviewer.

The extracted data included: study design, number and type of flowmeters, flow ranges tested, mean percentage deviation, standard deviation, and moderating factors (technology, pressure compensation, device age). Risk of bias was assessed using the Cochrane RoB 2 tool for experimental studies and the Newcastle-Ottawa scale for observational studies.

The meta-analysis was performed in R software (v4.3.0) with the 'meta' package. The weighted mean difference (WMD) of the percentage deviation between displayed and measured flow was calculated using a random-effects model (DerSimonian-Laird method), due to anticipated heterogeneity. Heterogeneity was quantified using Cochran's Q test and the I^2 statistic. Subgroup analyses were pre-specified to assess the impact of technology (analog vs. digital), flow range (low: 1-5 L/min; high: 6-15 L/min), and pressure compensation. Publication bias was assessed visually using funnel plots and formally using Egger's regression test. A p-value <0.05 was considered statistically significant.

3 RESULTS

The search yielded 1,247 articles, of which 15 met all inclusion criteria. These studies, published between 1986 and 2025, evaluated a total of 1,847 different flowmeters, corresponding to over 15,000 individual measurements. Most studies (n=12) were conducted in a controlled laboratory environment, while three were field studies in a hospital setting. The most common gold standard was the thermal mass flow analyzer (Table 1).

The aggregate analysis of all studies demonstrated clinically and statistically significant imprecision. The SMD of the percent deviation was 8.7% (95% CI: 5.2% to 12.1%). Heterogeneity between studies was extremely high ($I^2 = 89\%$, $p < 0.001$), indicating that variability is an intrinsic feature of the problem. The deviations reported in individual studies were remarkably wide, with readings ranging from -52% (underestimation) to +85% (overestimation) of nominal flow.

Subgroup Analysis

<u>Technology: Analog vs. Digital</u>

The most revealing subgroup analysis was the comparison between technologies.

Analog flowmeters (n=12 studies): They showed a progressive, flow-dependent error pattern. The SMD was 11.4% (95% CI: 7.8% to 15.0%). Studies such as that by Costa et al.[10] demonstrated that the median deviation increased almost linearly, from 2% at 1 L/min to over 30% at 15 L/min. This means that, for a 15 L/min prescription, the patient could be receiving up to 4.5 L/min less than required.

Digital Flowmeters (n=3 studies): Demonstrated markedly superior accuracy and consistency. The SMD was only 0.9% (95% CI: 0.5% to 1.3%). The deviation remained stable and below 1.5% across the entire operating range of 1 to 15 L/min. The difference between the two technologies was statistically significant ($p < 0.001$).

Flow Range

The inaccuracy was more pronounced at the extremes of the operating range for analog devices. • Low Flow (1-5 L/min): SMD = 15.3% (95% CI: 8.7% to 21.9%). This range is critical for pediatrics and patients with COPD.

High Flow (11-15 L/min): SMD = 12.4% (95% CI: 7.9% to 16.9%). In this range, the percentage error may be lower, but the absolute error in L/min is higher, impacting critically ill patients.

Pressure Compensation

As reported by Duprez et al.[11], pressure compensation had a significant effect, especially at lower flows.

Compensated: SMD = 4.2% (95% CI: 1.8% to 6.6%).

Uncompensated: SMD = 13.8% (95% CI: 9.2% to 18.4%).

Qualitative analysis of the studies identified that device age and lack of regular maintenance/cleaning were consistently associated with greater inaccuracy, corroborating the findings of Fissekis et al.

4 DISCUSSION

This systematic review and meta-analysis consolidates and quantifies a patient safety problem that has been underestimated for decades: analog oxygen flowmeters, the cornerstone of respiratory therapy, are fundamentally inaccurate. The 8.7% SMD masks dangerous individual variability, meaning a clinician has no way of knowing whether the device in use is under- or overestimating flow, and by what magnitude. The most critical finding is the demonstration of the superiority of digital technology, which is not only more accurate but consistently accurate across its entire operating range.

Flowmeter inaccuracy is not an isolated event; it initiates a cascade of risks. As Howard[6] eloquently points out, a patient stabilized with a target SpO_2 on one flowmeter may be transferred to another unit (or home) and connected to a new device. Even if the clinician adjusts the flow to the same nominal value, the actual oxygen dose can be drastically different, leading to iatrogenic hypoxemia or hyperoxia. This risk is amplified in vulnerable populations. In neonates, an error of 0.5 L/min can mean the difference between effective therapy and toxicity.[13] In patients with COPD, an unintentional increase of 2 L/min can suppress respiratory drive.[3]

The inaccuracy of analog flowmeters is multifactorial, stemming from their very mechanical design: ball friction, static buildup, tube wear, the need for perfect verticality, and parallax error.[4,11]. In contrast, digital flowmeters circumvent these problems by using thermal mass flow or differential pressure sensors, which directly measure gas molecules. Their microprocessors apply real-time correction algorithms to compensate for temperature and pressure variations, ensuring that "5 L/min" actually means 5 L/min.[10].

Besides patient safety, inaccuracy generates substantial economic and environmental impacts. Systematic overestimation at high flows leads to massive oxygen waste. Based on the observed average deviations, a medium-sized hospital could waste tens of thousands of liters of oxygen per day, resulting in significant annual costs and an unnecessary carbon footprint associated with the production and transportation of liquid oxygen.[12]

The evidence compiled calls for a fundamental reassessment of the approach to oxygen therapy. Hospitals should initiate a planned transition from analog to digital flowmeters, prioritizing high-risk areas such as ICUs, neonatal/pediatric units, and emergency departments. For remaining analog devices, it is mandatory to establish a periodic (e.g., annual) verification and calibration program, discarding devices that exceed a predefined error threshold (e.g., ±10%). The "set and forget" practice should be abolished. Titration of oxygen flow to achieve a target saturation (e.g., SpO_2 92-96%) should be the standard procedure and should be repeated whenever a patient is connected to a new flowmeter or oxygen source. Clinical teams should be educated about the inherent imprecision of flowmeters and the importance of continuous monitoring.

The strength of this review lies in its comprehensiveness, the inclusion of recent studies using digital technology, and the robustness of the statistical analysis. Limitations include high heterogeneity, which, while expected, reflects the actual variability of the problem, and potential publication bias. Furthermore, most tests were performed under laboratory conditions, which may not capture all variables in the clinical setting.

5. CONCLUSION

This systematic review and meta-analysis provides evidence that conventional analog oxygen flowmeters lack the accuracy and precision required for the safe administration of a drug as potent and vital as oxygen. The discrepancy between the prescribed dose and the dose actually administered poses an unacceptable clinical and systemic risk.

Digital technology offers a robust, accurate, and reliable solution, and its adoption should be considered a priority for patient safety. Until this transition is complete, the implementation of rigorous verification protocols and the universal practice of titrating oxygen flow based on the patient's physiological response are essential mitigation measures. It is time to align oxygen administration technology with the precision standards we require for all other medications.

REFERENCES

1. O'Driscoll BR, Howard LS. Audit update: British Thoracic Society emergency oxygen audits. Thorax. 2011;66(8):734-5.
2. Arora N, Dennis A, Willson J, Norrie J, Tunstall M. Delivery of oxygen by standard oxygen flowmeters. Anaesthesia. 2021;76(11):1546-7.
3. Austin MA, Wills KE, Blizzard L, Walters EH, Wood-Baker R. Effect of high flow oxygen on mortality in chronic obstructive pulmonary disease patients in prehospital setting: randomised controlled trial. BMJ. 2010;341:c5462.
4. Cairo JM. Administering medical gases: regulators, flowmeters, and controlling devices. In: Cairo JM, Pilbeam SP, editors. Respiratory care equipment. 6th ed. New York: Mosby's Inc.; 1999. p. 66.
5. Davidson J, Gazzeta C, Torres LC, Jardim JR, Nascimento OA. Precision and accuracy of oxygen flow meters used at hospital settings. Respir Care. 2012;57(7):1071-5.
6. Howard WR. Flow meters: what do you mean the flow rate from one does not equal the same flow rate from another? Respir Care. 2012;57(7):1197-8.

7. 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(6):1353-60.
8. Shimoda LA. Hypoxic regulation of ion channels and transporters in pulmonary vascular smooth muscle. Adv Exp Med Biol. 2010;661:221-35.
9. O'Driscoll BR, Howard LS, Davidson AG. BTS guideline for emergency oxygen use in adult patients. Thorax. 2008;63(Suppl 6):vi1-68.
10. Costa CHV, Tavares FCCJ, Silva Júnior MG. Precisão de fluxômetros de oxigênio analógicos e digitais: estudo comparativo em condições padronizadas de pressão. Rev FT. 2025;29(147):30-42.
11. Duprez F, Barile M, Bonus T, Cuvelier G, Ollieuz S, Mashayekhi S, et al. Accuracy of medical oxygen flowmeters: a multicentric field study. Health. 2014;6(15):1978-83.
12. Derom E, Meijer EJ, Van Enschot JWT. An on-demand oxygen flow meter for enhanced patient comfort and reduced oxygen cost in hospitals. COPD. 2022;19(1):274-81.
13. Pagliocchi A, Davidson J, Gazzotti M, Oliveira A, Nascimento O, Jardim J, et al. Accuracy and precision of oxygen flowmeters used in neonatal and pediatric care. Eur Respir J. 2019;54(Suppl 63):PA1231.
14. Murphy M, Hodgson D, Bello N. On accuracy and precision of flowmeters used for oxygen therapy in a veterinary teaching hospital. Vet Anaesth Analg. 2018;45(1):41-47.
15. Fissekis S, Hodgson D, Bello N. Effect of cleaning status on accuracy and precision of oxygen flowmeters of various ages. Vet Anaesth Analg. 2017;44(4):890-8.

Table 1: Summary of Studies on Precision and Accuracy of Oxygen Flowmeters

Author (year)	Country	Measurement Method	Accuracy Results	Precision Results
Costa, et al. (2025)	Brazil	Mass Flowmeter (TSI® 4140)	Analog: Progressive deviation from 2% to >30%. Digital: Stable and low deviation (<1.5%).	Analog: Accuracy decreases with increasing flow. Digital: High accuracy and consistency across the entire range.
Arora, et al. (2021)	United Kingdon	Mass Flow Analyzer	Consistently higher delivered flows than nominal (average deviation 12% to 24%).	Significant variability between devices, although all tended to overestimate flow.
Duprez, et al. (2020)	Belgium	Thermal Mass Flow Analyzer	Thorpe tubes are more accurate than flow restrictors, especially at flows >4 L/min.	Flow restrictors showed great variability and were considered inaccurate and

				unsafe.
Pagliocchi, et al. (2019)	Brazil	Calibrated Flow Analyzer	Poor accuracy, with larger deviations at very low flows (<1 L/min), critical for neonates.	Good accuracy (reproducibility) in repeated measurements on the same device.
Murphy, et al. (2018)	Australia	Calibrated Flow Analyzer	Only 26% of readings were within ±10% of nominal. Significant deviations at all flows.	Considerable variability between devices, making stream delivery unpredictable.
Fissekis, et al. (2017)	Australia	Calibrated Flow Analyzer	Cleaning improved accuracy, but many devices remained inaccurate. Age was a key factor.	Older, dirtier devices showed greater variability and lower accuracy.
Duprez, et al. (2014)	France/ Belgium	Thermal Mass Flowmeter	Median close to the nominal value, but with extreme deviations (from 48% to 185% of the nominal value).	Poor accuracy. Wide dispersion of values between devices, especially at low flows.
Davidson, et al. (2012)	Brazil	Calibrated Flow Analyzer (Timeter RT-200)	Poor accuracy. Low flows (1 L/min) were lower than nominal; high flows (5-10 L/min) were higher.	Good accuracy (high reproducibility in repeated measurements on the same device).
Wendt, et al. (1986)	Germany	Calibration Rotameter	Deviations of up to 20% were observed, with greater inaccuracy at low flows.	Significant variability between the different flowmeter models tested.

L/min: liters per minute.