Determining optimal air leak resolution criteria when using digital pleural drainage device after lung resection

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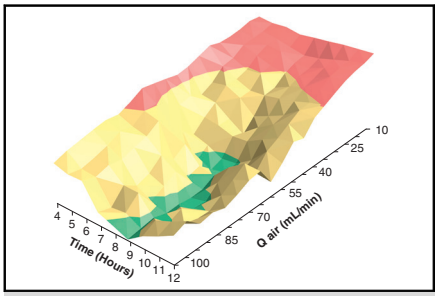
ABSTRACT

Objective: There is limited clinical evidence to support any specific parenchymal air leak resolution criteria when using digital pleural drainage devices following lung resection. The aim of this study is to determine an optimal air leak resolution criteria, where duration of chest tube drainage is minimized while avoiding complications from premature chest tube removal.

Methods: Airflow data averaged at 10-minute intervals was collected prospectively using a digital pleural drainage device (Thopaz; Medela) in 400 patients from 2015 to 2019. All permutations of air leak resolution criteria from <10 to 100 mL/minute for 4 to 12 hours were applied retrospectively to the pleural drainage data to determine air leak duration, and air leak recurrence frequency and volume. Air leak recurrence indicates potential for rather than occurrence of adverse events. Descriptive statistics were used to identify the optimal criteria based on patient safety (low frequency and volume of air leak recurrences), and efficiency (shortest initial air leak duration).

Results: The majority of the 400 patients underwent lobectomy (57% [227 out of 400]), wedge resections (29% [115 out of 400]), or segmentectomies (8% [32 out of 400]) for lung cancer (90% [360 out of 400]). An airflow threshold <50 mL/minute resulted in longer air leak duration before meeting the criteria for air leak resolution ($P < .0001$). Air leak recurrence frequency and volume were greater in patients with a monitoring period <8 consecutive hours ($P < .0001$).

Conclusions: When using a digital pleural drainage device, a postoperative air leak resolution criteria <50 mL/minute for 8 consecutive hours was associated with the best safety and efficiency profile. (JTCVS Open 2024;18:360-8)



Green indicates optimal air leak resolution criteria when using a digital pleural drainage device.

CENTRAL MESSAGE

A postoperative air leak that remains <50 mL/minute for 8 consecutive hours can be deemed resolved and carries minimal risk of recurrence after chest tube removal.

PERSPECTIVE

There is limited clinical evidence to support any specific parenchymal air leak resolution criteria when using digital pleural drainage devices after lung resection. Patients would benefit from an optimized air leak resolution criteria where duration of chest tube drainage is minimized while avoiding complications from premature chest tube removal.

Optimal chest tube management and timely removal are crucial to promoting early recovery after thoracic surgery.[1] Delayed or premature chest tube removal can lead to increased hospital length of stay and unnecessary health care expense.[2,3] A digital pleural drainage device connected to a chest tube provides continuous monitoring of any pulmonary parenchymal air leak. The technology is very sensitive and can detect small, clinically insignificant air

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leaks. An ongoing, clinically significant air leak is an important factor in determining whether or not a chest tube can be safely removed.[4] The duration of chest tube drainage can have a significant influence on length of stay following pulmonary surgery.[5] Although a small air leak may be detectable using a digital pleural drainage device, it is considered clinically resolved when the flow of air remains below an arbitrary threshold for a prescribed amount of time.[6] To our knowledge, there is no evidence to support the health care teams in selecting one criteria over another, and thus, there is considerable variability in what is considered as an acceptable airflow threshold and time interval for air leak resolution.[3,7-11] This research aimed to identify optimal air leak resolution criteria for chest tube management when using digital pleural drainage device following lung resection. Optimizing the air leak resolution criteria can help minimize the duration of chest tube drainage while avoiding potential complications due to premature chest tube removal. We hypothesized that it would be safe and efficient to liberalize the air leak resolution criteria currently used at our institution (air leak <30 mL/minute for 8 hours).

METHODS

The Ottawa Health Science Network-Research Ethics Board approved the study protocol and publication of data (reference No. 20180555-01H; approved May 23, 2018). The patients provided informed written consent for the publication of the study data.

Digital Data Collection

Patients older than age 18 years who underwent elective, sublobar, or lobar pulmonary resection for benign or neoplastic disease, for whom digital pleural drainage data were available for analysis, were included in this study. Recorded pleural drainage data were available for retrieval from the digital pleural drainage device (Thopaz; Medela) only once the chest tube was removed and the device disconnected from the patient. Using a proprietary software (ThopEasy Plus), the electronic airflow measurements were then converted into an electronic file format suitable for automated processing using a relational database software (MS Access; Microsoft Corp). The patient population in this study was subject to a standardized postoperative care pathway prescribing a pleural pressure setting of -8 cm H_2O. This setting was selected based on the manufacturer's recommendations as equivalent to water seal on analog pleural drainage devices. Using a sensor feedback loop, the device can apply a variable amount of suction to maintain this target pleural pressure. In total, airflow data were collected prospectively for 400 patients from 2015 to 2019. A total of 1808 patient-days of data were collected.

Outcomes

Any air leak resolution criteria consists of 2 variables: airflow threshold and duration of monitoring. All possible permutations of air leak resolution criteria were created by combining airflow thresholds ranging from 10 mL/minute to 100 mL/minute at 5 mL/minute intervals (19 unique values) and time intervals ranging from 4 to 12 hours at 1-hour intervals (9 unique values). In total, 171 (19×9) unique air resolution criteria were analyzed to determine the initial air leak duration, the air leak recurrence frequency, and the air leak recurrence volume.

In this article, *efficiency* is represented by the time from surgery to time for candidacy for chest tube removal based on the air leak criteria being evaluated. We defined the initial air leak duration as the time between the end of surgery and the time of the air leak resolution. We defined *safety* as the frequency of air leak recurrences and volume of those air leak recurrences because premature removal of a chest tube, or removal before the resolution of an air leak, may lead to adverse events (eg, pneumothorax, uncontrolled subcutaneous emphysema, and patient discomfort) and is therefore unsafe. This, in turn, may delay discharge and/or require intervention such as chest tube reinsertion. Air leak recurrence was defined as an increase in air leak above the airflow threshold being evaluated occurring after the air leak resolution criteria were met. Because all patients had indwelling chest drains, air leak recurrence implies the potential for an adverse event (eg, pneumothorax or subcutaneous emphysema) if the chest drain had been removed after the criteria were met, rather than its actual occurrence. We compared the 171 air leak resolution criteria based on efficiency (initial air leak duration) and safety (air leak recurrence frequency and volume) to determine whether or not there is a range of criteria with significantly better outcomes.

Statistical Analysis

We analyzed the available recorded digital drainage data from lung resection patients who were treated according to our institutional postoperative care protocols and had their chest tube removed once our current air leak resolution criteria was met (<30 mL/minute for 8 hours). We then implemented 171 different air leak resolution criteria based on permutations of airflow threshold and time intervals to evaluate the influence on air leak duration and air leak recurrence after resolution. These criteria were retrospectively applied to the digital data of 400 patients. For each of our 3 outcomes (initial air leak duration, air leak recurrence frequency, and air leak recurrence volume), the mean was calculated for each air resolution criteria. We standardized the results of the 3 outcomes, which had distinct units of measurement, to allow for a mathematical comparison. To standardize the results, the z score was calculated for each outcome using the formula:

z = (value of the outcome–mean of the distribution)/SD of the distribution

Once all 3 outcome results were standardized, we determined the safety of each criteria by calculating the mean of air leak recurrence frequency and air leak recurrence volume. By combining the safety and efficiency results, we created a comprehensive table that incorporates all 3 outcomes, enabling a more complete analysis of the data. To facilitate the interpretation of these data, we created 3-dimensional heatmaps with monitoring duration on the x-axis, airflow threshold on the y-axis, and the standardized safety and efficiency results on the z-axis.

We also identified the safest and most efficient criteria for each outcome by using the median to separate the criteria results into 2 groups. Then, using 2-tailed t tests, we assessed whether or not the safest and most efficient criteria demonstrated any statistically significant differences compared with those remaining. The analyses were performed with the intent to identify the air leak resolution criteria that maximizes both safety and efficiency.

RESULTS

From September 2015 to April 2019, 400 patients had digital pleural drainage data available for analysis. A total of 1808 patient-days of airflow data were collected. The majority of the 400 patients underwent lobectomies (57% [227 out of 400]), wedge resections (29% [115 out of 400]), or segmentectomies (8% [32 out of 400]) for lung cancer (90% [360 out of 400]). Most patients (67% [266 out of 400]) experienced an air leak recurrence for at least 1 of the air leak resolution criteria evaluated. In Table 1,

percentages are enclosed in parentheses and minimum and maximum values of each characteristic are presented. During our study period, 12 out of 400 patients had a chest tube reinserted or an additional chest tube inserted due to complications (eg, increasing pneumothorax or subcutaneous emphysema).

The first measured outcome of this study was the initial air leak duration (ie, time from surgery to time of air leak resolution). The median of all identified initial air leak duration was 23 hours (interquartile range [IQR], 20-26 hours). The initial air leak duration was found to be longer when using air leak resolution criteria that had higher observation periods or lower airflow thresholds. The initial air leak duration was significantly shorter for air leak resolution criteria that had air drainage thresholds of 50 mL/minute or more ($P < .0001$). The average initial air leak duration for each air leak resolution criteria can be found in Table 2.

The second measured outcome of this study was the frequency of air leak recurrences (ie, an increase of airflow beyond the established threshold after the air leak resolution criteria has been satisfied). The median of all identified air leak recurrence frequency was 2 recurrences (IQR, 1-2 recurrences). The frequency of air leak recurrences was found to be higher when using air leak resolution criteria that had lower time threshold, or lower airflow threshold. Air leak recurrence frequency was significantly lower for air leak resolution criteria that had 8 hours of monitoring or more ($P < .0001$). The average frequency of air leak recurrences for each air leak resolution criteria can be found in Table 3.

The third measured outcome of this study was the duration of air leak recurrences. The median of all identified air leak recurrence volumes is 20 L (IQR, 11-39 L). The duration of air leak recurrences was found to be higher when using air leak resolution criteria that had lower time thresholds or higher airflow thresholds. Air leak recurrence volume is significantly lower for air leak resolution criteria that have 8 hours of monitoring or more ($P < .0001$). The average volume of air drained from air leak recurrences for each air leak resolution criteria can be found in Table 4.

The safest air leak resolution criteria (lowest frequency and volume of air leak recurrences) were found to have a higher observation period, irrespective of airflow threshold. The safest criteria, those with air leak recurrence frequency and volume below the median, always required a minimum of 8 hours of monitoring. Air leak resolution criteria that required 8 or more hours of monitoring are safer than $\leq$7 hours ($P < .0001$). The standardized average of air leak recurrence frequency and air leak recurrence volume can be found in Table 5.

The safest and most efficient air leak resolution criteria (shortest initial air leak duration and lowest air leak recurrence frequency and volume) had time thresholds of 8 hours and airflow thresholds of 50 mL/minute. An overlay of the safest and most efficient criteria is highlighted in Figure 1.

The safety and efficiency heatmaps found in Figure 2 depict optimal air leak resolution criteria, with green representing the safest and most efficient values. Overlaying both heatmaps reveals the ideal criteria, marked in green, at the intersection of safety and efficiency.

We completed a subgroup analysis comparing lobectomy to wedge resections, which constitute the 2 largest subgroups of patients. For wedge resection patients (n = 115), the duration of initial air leak was shorter as would be expected but when we attempted to determine the safest criteria for these patients there was no recognizable pattern of air leak recurrence frequency and volume following the same methodology. As for lobectomy patients (n = 227), we observed clear patterns in the duration of the initial air leak and air leak recurrence frequency and volume. With this subgroup of patients, the optimal criteria emerging was airflow <45 mL/minute for 7 hours.

Demographics

TABLE 1. Characteristics of the patient cohort

Characteristic	Cohort (N = 400)
Age (y)	65 (19-87)
Female gender	225 (56)
BMI	27 (10-49)
Smoker	265 (66)
Pack-years	20 (0-120)
FEV1%	75 (0-139)
DLCO%	64 (0-125)
Pleural adhesions	27 (7)
Diagnosis	
NSCLC	287 (72)
Carcinoid	38 (10)
Cancer metastatic to lung	35 (9)
Other	39 (10)
Primary procedure	
Lobectomy	227 (57)
Wedge	115 (29)
Segmentectomy	32 (8)
Other	26 (7)

Values are presented as average (min-max) or n (%). *BMI*, Body mass index; *FEV1%*, percent predicted forced expiratory volume in 1 second; *DLCO%*, percent predicted diffusion capacity for carbon monoxide; *NSCLC*, non–small cell lung cancer.

Initial Air Leak Duration

TABLE 2. Average initial air leak duration (hours) for each air leak resolution criteria (N = 400 patients)

Airflow threshold criteria (mL/min)	Minimum period during which air leak is less than airflow threshold (h)								
	4	5	6	7	8	9	10	11	12
<10	22.9*	24.2	25.7	27.2	29.1	30.3	31.6	32.9	33.8
<15	23.0	23.5	24.5	25.9	27.1	28.2	29.5	31.0	32.3
<20	21.5	23.5	24.4	25.7	26.8	28.2	29.5	30.9	32.3
<25	20.3	22.2	23.9	25.0	26.4	27.3	28.6	29.6	31.2
<30	19.4	21.2	22.4	23.5	25.1	26.6	27.9	28.7	30.0
<35	19.2	20.8	21.8	22.6	24.4	25.7	26.8	27.6	28.8
<40	18.8	19.7	21.0	21.9	23.4	24.8	26.0	27.5	28.3
<45	18.4	19.6	20.6	21.4	23.0	24.1	25.4	26.9	27.2
<50	17.6	18.7	19.8	21.2	22.8	23.9	24.8	26.1	27.1
<55	17.3	18.3	20.0	20.8	22.4	23.3	24.2	25.4	26.5
<60	17.0	18.2	19.5	20.4	22.0	22.8	23.9	24.8	25.8
<65	17.1	18.4	19.8	20.9	22.1	22.8	23.8	25.0	25.9
<70	16.5	17.9	19.3	20.6	22.3	22.6	23.6	24.7	25.7
<75	16.4	17.4	18.7	20.0	21.7	22.6	23.5	24.6	25.5
<80	16.4	17.8	18.6	19.6	21.2	22.4	23.3	23.9	24.9
<85	15.5	17.0	17.8	18.9	20.4	21.5	22.9	23.9	24.9
<90	15.1	16.8	18.0	19.3	20.8	21.6	22.6	23.8	24.8
<95	14.7	16.4	17.7	18.8	20.3	21.4	22.7	24.1	25.1
<100	14.3	16.1	17.0	18.5	20.1	21.3	22.4	23.9	24.7

*The average duration of the postoperative air leak was 22.9 hours when "airflow <10 mL/min for at least 4 hours" was used as the air leak resolution criteria.

Table 2 outlines the average initial air leak duration based on various air leak resolution criteria we tested. For example, an air leak criteria <10 mL/minute for 4 consecutive hours would have resulted in resolution of the initial air leak after 22.9 hours. The median of all identified initial air leak duration is 23 hours (IQR, 20-26 hours). A trend can be observed in which lower air leak durations are associated with air leak resolution criteria that have both shorter monitoring periods and higher airflow thresholds (bottom left corner of Table 2). The initial air leak duration was significantly shorter for the air leak resolution criteria that had an airflow threshold of 50 mL/minute or more ($P < .0001$). Initial air leak duration will inherently be higher when applying air leak resolution criteria with a longer monitoring durations.

Air Leak Recurrence Frequency

Table 3 outlines the average frequency of air leak recurrences based on various air leak resolution criteria being tested (n = 400). A trend can be observed in which lower air leak recurrence frequency is captured by air leak resolution criteria that have both increased monitoring periods and increased air drainage thresholds (bottom right corner of Table 3). The median of all identified air leak recurrence frequency was 2 recurrences (IQR, 1-2 recurrences). Air leak recurrence frequency is significantly lower for air leak resolution criteria that have 8 hours of monitoring or more ($P < .0001$).

Air Leak Recurrence Volume

Table 4 outlines the average volume of air leak recurrences based on various air leak resolution criteria being tested (n = 400). A trend can be observed in which lower air leak recurrence volume is captured by air leak resolution criteria that have both increased monitoring periods and decreased air drainage thresholds (top right corner of Table 4). The median of all identified air leak recurrence volumes is 20 L (IQR, 11-39 L). Air leak recurrence volume is significantly lower for air leak resolution criteria that have 8 hours of monitoring or more ($P < .0001$).

Air Leak Recurrence Frequency and Volume Overlay

Table 5 outlines the standardized combined results of the air leak recurrence frequency (Table 3) and air leak recurrence volume (Table 4). Values shown represent the standardized average of air leak recurrence frequency and air leak recurrence volume. The data were

TABLE 3. Average frequency of air leak recurrences for each air leak resolution criteria (N = 400 patients)

Airflow threshold criteria (mL/min)	Minimum period during which air leak is less than airflow threshold (h)								
	4	5	6	7	8	9	10	11	12
<10	3.09*	2.70	2.52	2.12	2.00	1.82	1.62	1.38	1.36
<15	3.08	2.59	2.26	1.86	1.72	1.52	1.38	1.24	1.19
<20	2.88	2.33	2.19	1.91	1.67	1.33	1.25	1.13	0.99
<25	2.99	2.54	2.10	1.78	1.60	1.45	1.32	1.24	0.98
<30	2.85	2.50	2.16	2.02	1.63	1.47	1.31	1.26	1.07
<35	3.05	2.47	2.12	1.89	1.73	1.53	1.33	1.28	1.10
<40	2.72	2.40	2.27	2.05	1.58	1.42	1.33	1.23	1.04
<45	2.58	2.24	2.10	1.82	1.51	1.44	1.37	1.20	0.96
<50	2.64	2.25	2.07	1.82	1.62	1.39	1.31	1.21	1.06
<55	2.57	2.09	1.82	1.71	1.49	1.34	1.26	1.20	0.86
<60	2.59	2.18	1.86	1.68	1.47	1.37	1.25	1.11	0.86
<65	2.61	2.10	1.85	1.67	1.43	1.30	1.24	1.18	0.93
<70	2.48	2.16	1.94	1.62	1.37	1.20	1.18	1.06	0.95
<75	2.30	2.01	1.86	1.64	1.38	1.15	1.09	1.00	0.89
<80	2.34	1.98	1.79	1.57	1.38	1.23	1.14	1.06	0.95
<85	2.32	1.88	1.71	1.57	1.37	1.25	1.16	1.02	0.95
<90	2.33	1.82	1.71	1.58	1.46	1.32	1.16	1.08	0.96
<95	2.31	1.78	1.66	1.52	1.42	1.30	1.23	1.12	1.01
<100	2.33	1.91	1.91	1.60	1.40	1.27	1.20	1.09	1.02

*The average frequency of air leak recurrences was 3.09 when "airflow <10 mL/min for at least 4 hours" was used as the air leak resolution criteria.

TABLE 4. Average volume (L) of air drained from air leak recurrences for each air leak resolution criteria (N = 400 patients)

Airflow threshold criteria (mL/min)	Minimum period during which air leak is less than airflow threshold (h)								
	4	5	6	7	8	9	10	11	12
<10	38.8*	26.8	21.6	16.4	8.3	6.0	5.7	5.6	5.6
<15	40.5	28.4	21.9	17.3	9.5	9.0	8.6	8.3	7.9
<20	41.4	28.9	23.3	18.1	9.9	9.3	9.0	8.8	7.7
<25	42.0	29.2	23.5	18.1	10.2	9.9	9.6	9.4	8.4
<30	51.8	30.1	23.7	19.4	10.5	9.7	9.5	9.1	8.5
<35	52.4	29.8	24.2	19.6	11.0	9.7	9.3	9.0	8.5
<40	51.8	29.9	24.8	19.9	11.6	10.9	10.3	9.9	8.6
<45	53.5	31.6	24.6	19.4	11.4	11.0	10.9	9.7	8.4
<50	55.7	42.0	25.1	20.6	11.9	11.1	10.8	10.2	9.3
<55	62.4	48.2	26.5	21.1	12.1	10.9	10.7	10.3	9.0
<60	65.3	51.2	33.5	21.3	12.2	11.8	11.1	10.5	9.5
<65	65.7	59.8	42.5	28.9	19.5	17.8	17.4	17.0	15.8
<70	66.1	62.0	52.9	28.7	19.2	17.6	17.5	16.7	16.1
<75	65.9	62.0	53.8	39.1	29.6	18.9	17.3	16.7	16.1
<80	65.7	61.7	53.8	38.6	29.9	19.2	17.6	17.4	16.8
<85	71.2	66.3	58.5	42.7	34.3	24.4	23.5	18.7	18.4
<90	71.1	66.0	58.3	42.9	34.5	24.6	23.3	18.5	18.2
<95	71.8	65.6	58.0	43.4	35.0	25.1	24.6	19.7	19.4
<100	71.4	66.8	59.3	44.1	35.4	25.6	25.0	20.1	19.9

*The average total volume of air leak recurrences was 38.8 liters when "airflow <10 mL/minute for at least 4 hours" was used as their air leak resolution criteria.

TABLE 5. Standardized combined results of the air leak recurrence frequency and volume (N = 400 patients)

Airflow threshold criteria (mL/min)	Minimum period during which air leak is less than airflow threshold (h)								
	4	5	6	7	8	9	10	11	12
<10	1.64*	0.96	0.65	0.14	−0.18	−0.41	−0.60	−0.82	−0.84
<15	1.67	0.90	0.42	−0.07	−0.41	−0.61	−0.74	−0.89	−0.94
<20	1.51	0.67	0.39	0.00	−0.44	−0.78	−0.85	−0.97	−1.13
<25	1.63	0.87	0.32	−0.12	−0.50	−0.64	−0.77	−0.85	−1.12
<30	1.76	0.86	0.38	0.14	−0.46	−0.63	−0.78	−0.84	−1.04
<35	1.96	0.82	0.36	0.02	−0.35	−0.58	−0.78	−0.83	−1.01
<40	1.64	0.77	0.51	0.18	−0.48	−0.65	−0.75	−0.85	−1.06
<45	1.55	0.66	0.34	−0.05	−0.55	−0.62	−0.70	−0.88	−1.14
<50	1.67	0.94	0.33	−0.02	−0.43	−0.67	−0.75	−0.87	−1.02
<55	1.78	0.96	0.14	−0.11	−0.55	−0.72	−0.80	−0.87	−1.22
<60	1.87	1.12	0.36	−0.14	−0.56	−0.67	−0.80	−0.95	−1.20
<65	1.90	1.27	0.58	0.06	−0.41	−0.58	−0.64	−0.71	−0.97
<70	1.79	1.39	0.94	0.01	−0.48	−0.67	−0.69	−0.83	−0.95
<75	1.62	1.25	0.89	0.30	−0.19	−0.69	−0.78	−0.88	−1.00
<80	1.65	1.21	0.83	0.23	−0.18	−0.61	−0.73	−0.81	−0.92
<85	1.78	1.24	0.88	0.33	−0.08	−0.44	−0.56	−0.81	−0.88
<90	1.79	1.18	0.87	0.35	0.01	−0.38	−0.56	−0.76	−0.88
<95	1.79	1.13	0.82	0.30	−0.01	−0.38	−0.46	−0.69	−0.80
<100	1.79	1.29	1.09	0.39	−0.02	−0.40	−0.48	−0.71	−0.78

*For the air leak resolution criteria of airflow <10 mL/min for at least 4 hours, the z score for air leak recurrence frequency and volume is 1.64 (lower is better).

standardized by calculating the z score (z = [value of the outcome–mean of the distribution]/SD of the distribution) for air leak recurrence frequency and volume. Air leak resolution criteria that required 8 or more hours of monitoring are safer, specifically in terms of lower frequency and volume of air leak recurrences, than the remaining criteria ($P < .0001$).

Combined Standardized Data of All 3 Measured Outcomes

Figure 1 outlines the combined standardized data of air leak recurrence frequency, air leak recurrence volume, and initial air leak duration. Values shown represent the standardized average of air leak recurrence frequency, air leak recurrence volume, and initial air leak duration. The

Airflow threshold criteria (mL/min)	Minimum period during which air leak is less than airflow threshold (h)								
	4	5	6	7	8	9	10	11	12
< 10	*0.90	0.69	0.70	0.60	0.65	0.67	0.72	0.75	0.85
< 15	0.93	0.56	0.43	0.32	0.28	0.30	0.38	0.49	0.61
< 20	0.67	0.44	0.39	0.34	0.23	0.21	0.32	0.43	0.52
< 25	0.58	0.39	0.30	0.18	0.14	0.17	0.26	0.34	0.39
< 30	0.54	0.26	0.14	0.14	0.01	0.10	0.17	0.23	0.29
< 35	0.63	0.20	0.06	−0.03	−0.03	0.01	0.04	0.10	0.15
< 40	0.40	0.03	0.05	−0.03	−0.22	−0.13	−0.04	0.08	0.06
< 45	0.30	−0.05	−0.10	−0.22	−0.30	−0.20	−0.09	−0.01	−0.11
< 50	0.27	0.00	−0.20	−0.23	−0.26	−0.26	−0.20	−0.10	−0.06
< 55	0.30	−0.03	−0.29	−0.33	−0.37	−0.36	−0.30	−0.19	−0.24
< 60	0.31	0.03	−0.22	−0.39	−0.44	−0.39	−0.34	−0.30	−0.32
< 65	0.33	0.15	−0.06	−0.22	−0.33	−0.35	−0.26	−0.15	−0.18
< 70	0.21	0.15	0.08	−0.28	−0.35	−0.42	−0.31	−0.24	−0.19
< 75	0.10	0.02	−0.03	−0.19	−0.27	−0.42	−0.38	−0.30	−0.24
< 80	0.11	0.04	−0.07	−0.28	−0.32	−0.41	−0.37	−0.34	−0.27
< 85	0.07	−0.04	−0.15	−0.31	−0.35	−0.42	−0.32	−0.33	−0.25
< 90	0.03	−0.10	−0.12	−0.26	−0.26	−0.37	−0.35	−0.32	−0.26
< 95	−0.02	−0.18	−0.19	−0.34	−0.33	−0.40	−0.29	−0.24	−0.18
< 100	−0.06	−0.13	−0.12	−0.33	−0.36	−0.43	−0.33	−0.29	−0.22

FIGURE 1. Standardized combined results of initial air leak duration, air leak recurrence frequency, and air leak recurrence volume (N = 400 patients). *For the air leak resolution criteria of airflow <10 mL/minute for at least 4 hours, the z score for initial air leak duration, air leak recurrence frequency, and air leak recurrence volume is 0.90 (lower is better).

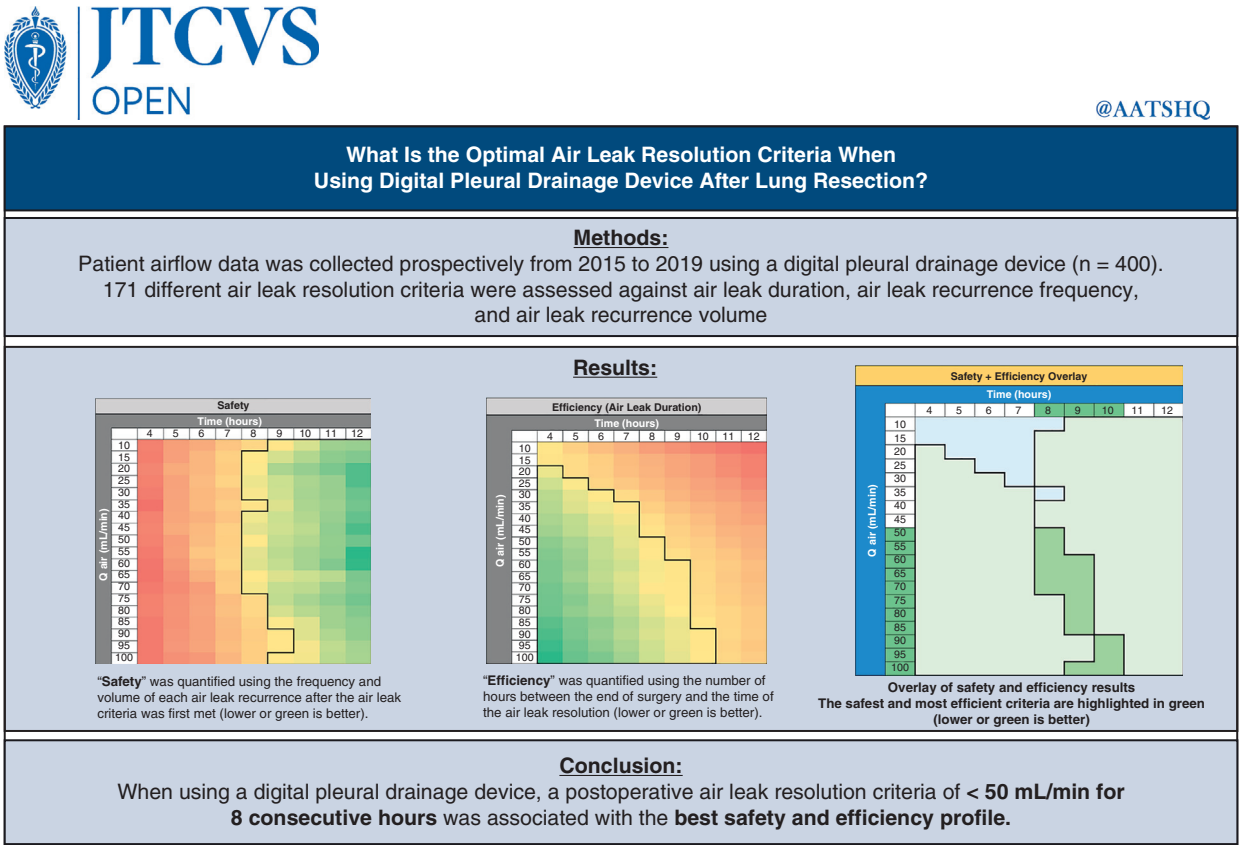

FIGURE 2. Graphical abstract. The safety and efficiency heatmaps depict optimal air leak resolution criteria, with *green* representing the safest and most efficient values. Overlaying both heatmaps reveals the ideal criteria, marked in *green*, at the intersection of safety and efficiency.

data were standardized by calculating the z score ($z = [$value of the outcome–mean of the distribution$]$/SD of the distribution). In Figure 1, lower numbers are safer and more efficient. The cells highlighted in light green are the most efficient criteria. The cells highlighted in grey are the safest criteria. The dark green cells represent the air leak resolution criteria that are amongst the safest and most efficient criteria. Based on Figure 1, the most optimal air leak resolution criteria was an airflow threshold <50 mL/minute for 8 consecutive hours.

DISCUSSION

Digital pleural drainage systems can help reduce interobserver variability and standardize the assessment of pulmonary air leaks following lung resection.[12] Although bedside air leak assessment is a commonly performed task in the care of patients with chest tubes, there is considerable variability in the criteria and methods used to determine whether or not an air leak has resolved.[3,7-10,13] Air leak resolution criteria continue to vary greatly across the literature. This study is an attempt to correlate digital pleural drainage data and outcomes to develop evidence in support of pulmonary air leak resolution criteria that achieve the best balance between safety and efficiency. The results have identified combination of airflow rates and periods of observation (ie, airflow <50 mL/minute for at least 8 consecutive hours) where safety and efficiency were maximized.

This is consistent with our hypothesis that the air leak resolution criteria we currently use (<30 mL/minute for 8 hours) can be safely liberalized, with respect to airflow threshold, without compromising patient safety at our institution. Our results reveal that initial air leak duration was significantly longer for criteria with airflow thresholds below 50 mL/minute and therefore should be avoided. Additionally, air leak recurrence frequency and volume significantly increased when monitoring periods were shorter than 8 hours. Therefore, based on our results, the airflow threshold can be safely increased to 50 mL/minute whilst adhering to same observation period of 8 hours. This criteria maximizes both safety (reduction in air leak recurrence frequency and volume) and efficiency (reduction in initial air leak duration). When interpreting our results in Table 4, it is important to keep in mind that some recurrent air leaks may be characterized by low airflow persisting over a long period of time. This could lead to a substantial total volume of air drained per recurrence and thus some values may appear abnormally high from a clinical point of view. These specific types of recurrences would only

occur with air leak resolution criteria permutations using the low end of the range of airflow thresholds evaluated. Therefore, they may not always be clinically significant because it is known that chest tubes can be safely removed with an ongoing, measurable low-flow air leak (eg, <30 mL/minute), suggesting that the pleural space and soft tissues have physiologic properties allowing reabsorption of air at an equal or greater rate. The 2 components of the air leak resolution criteria are the airflow threshold and monitoring hours. As shown in Table 5, the safety of the air leak resolution criteria appears to be largely driven by the duration of the monitoring period as opposed to the airflow threshold used. In other words, changes in airflow threshold yielded minimal improvement in safety when compared with changes in monitoring period (longer monitoring periods were safer). On the other hand, as shown in Table 2, the efficiency of an air leak resolution criteria appears to be largely driven by the airflow threshold used as opposed to the duration of the monitoring period. In other words, changes in monitoring period yielded minimal improvements in efficiency when compared with changes in airflow thresholds (higher airflow thresholds were more efficient). There appears to be no additional gain in safety by increasing the monitoring period for more than 8 hours because this artificially increases initial air leak duration with no reduction in the risk of air leak recurrence frequency and volume. Similarly, we did not identify a significant improvement in safety by restricting the airflow threshold below 50 mL/minute. The only consequence of using lower thresholds was a penalty in efficiency from unnecessarily prolonged air leak duration.

It is important to implement any digital air leak resolution criteria in clinical practice while considering factors that may transiently or persistently affect a parenchymal air leak. For instance, the measured airflow may transiently or persistently decrease with sleep or increase with a leak in the system or at the chest tube site, physical activity, coughing spells, or chest physiotherapy. These factors may need to be taken into consideration when unexpected air leak flow variations are observed.

We would like to emphasize that any proposed pulmonary air leak resolution criteria is based on what is considered to be the appropriate balance between safety and efficiency in the management of chest tubes. We acknowledge that acceptable safety and efficiency thresholds may vary from surgeon to surgeon and are thus associated with some degree of subjectivity. The air leak criteria we propose has not yet been tested prospectively at our institution. In our retrospective analysis, we defined an air leak recurrence as an increase of airflow beyond the established threshold after the air leak resolution criteria has been satisfied. For safety reasons, we made the assumption that all recurrences identified could have clinically significant consequences for the patient.

Limitations of this study include the single-center design, and exclusive use of Thopaz, which may limit our ability to generalize the findings. Furthermore, the majority of patients included in the study were smokers who were diagnosed with non–small cell lung cancer and underwent lobectomies. These characteristics further limit the result's generalizability to the broader population. The digital pleural drainage data used in this research were obtained using a specific device. We acknowledge that the results may not apply to patients drained with other commercially available devices. We also acknowledge that our study is yet to be validated in a prospective cohort.

The digital devices were used routinely in all patients and not selectively. However, due to various factors (eg, device maintenance/repairs, failure to record, and logistics), not all digital data were available for analysis. This is unlikely to have caused major systematic bias. We have tested a subset of all the possible air leak resolution criteria within the selected range of airflow thresholds and observation periods. We realize that by using increments of 5 mL/minute and 1 hour we may have missed the best possible combination. We selected these intervals based on simplicity and on our experience with digital drainage devices, which tells us that airflows <30 mL/minute are typically not associated with a clinically significant air leak. Future prospective trials are needed to confirm the safety of the criteria range identified.

The digital air leak resolution criteria used during the study period and currently at our institution is airflow <30 mL/minute airflow for 8 consecutive hours. Our results were derived from a simulation of what would have happened if chest tube(s) had been removed soon after any of the other 170 air leak resolution criteria being evaluated were met. Therefore, the rate of clinically observed adverse events (eg, chest tube reinsertion) cannot be used as a basis for comparison or to predict what would have happened because of air leak recurrences identified in the digital pleural drainage data analyzed. The absence of clinic safety data on worsening pneumothorax or subcutaneous emphysema, or chest tube reinsertion, with each of the 170 other air leak resolution criteria evaluated is a reflection of insurmountable research logistical hurdles rather than a flaw in our study design. We selected air leak recurrence frequency and volume as reasonable surrogate outcomes because they are sine qua non to the occurrence of the aforementioned adverse events. The number of patients and resources required to find out what would have happened after any air leak recurrence identified at all possible air leak resolution criteria would be astronomical. From a safety standpoint, we have made the assumption that an air leak recurrence could potentially have adverse consequences for the patient.

We acknowledge that there was a small difference in optimal air leak resolution criteria when we confined the

analysis to lobectomy patients. We think that this difference of 5 mL/minute in airflow threshold and 1 hour in observation period is not clinically significant. However, we acknowledge that analyzing all resection types together may have introduced bias. Caution should be exercised in interpreting the results and introducing a new digital air leak resolution criteria to practice. Interpretation and clinical translation of the results should take this into account. Our intent was to maximize sample size and identify a range of criteria that would be potentially applicable to general practice, which typically includes a mix of different lung resections. We believe that developing a unified criteria for all resection types may facilitate clinical implementation and decrease the potential for errors due to mismatch between the air leak resolution criteria used and the type of resection performed.

Digital pleural drainage devices bring precision medicine to the management of the pleural space and given their benefits and potential, are likely to become more widespread. Although our results are only relevant to current and future users of this technology and may have limited applicability to current general practice, they represent a significant step forward in providing evidence-based guidance when selecting digital air leak resolution criteria for the management of patients with chest tubes.

CONCLUSIONS

Our findings suggest that a postoperative air leak that remains <50 mL/minute for 8 consecutive hours as indicated from a digital pleural drainage system can be deemed resolved and carries minimal risk of recurrence after chest tube removal. It is recommended to avoid an air leak resolution criteria with an airflow threshold below 50 mL/minute and refrain from monitoring patient for periods <8 consecutive hours because these conditions may contribute to prolonged air leak duration, increased air leak recurrences, and/or larger volumes of recurrent air leaks. In summary, we noted that shorter observation periods and lower flow thresholds were associated with an increased risk of recurrence that could translate to an increased risk of chest tube reinsertion. A prospective study design of selected air leak resolution criteria based on our work would help quantify this risk.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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Key Words: chest tube, air leak duration, air leak recurrence, air leak resolution criteria