

Algorithm for Automatic Forced Spirometry Quality Assessment: Technological Developments

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On-Line Supplement

Based on the comparison of the metric (M_j) with its related threshold (STh_i), a score value (S_n) is assigned to each criterion (C_n). Then, for each S_n a score threshold (STh_n) is defined in order to evaluate the quality of the criteria. The score of some criteria are jointly analyzed by summing their scores to be compared with a single score threshold. The automatic classification of the FS curves is determined by considering each score (or combination of some scores) and the respective score thresholds, as it is shown in the flow-chart of each zone.

Scores

Each score (S_n) is calculated as function of the metrics (M_n) of each criterion and the respective thresholds. When the criterion C_n condition is $M_n > th_{ni}$, $S_n = 100$ if $M_n > th_{ni}$ otherwise $S_n = 100 \frac{M_n}{th_{ni}}$. When the criterion C_n condition is $M_n < th_{ni}$, $S_n = 100$ if $M_n < th_{ni}$ otherwise $S_n = 100 \frac{th_{ni}}{M_n}$.

If a particular criterion uses more than one metric for defining its quality, the score of the criterion is calculated as the mean value of the scores of each metric.

Flowchart

Figure S1, S2, S3, S4 and S5 show the flowchart of the decision process of the entire algorithm, divided by zone.

Each block is assessed by a score (S_n) or a combination of scores compared with a score threshold (STh_n). On the left of the flowchart there is the main path followed by the curves that fulfill all the criteria. If all the criteria scores are above of respective thresholds a curve remains

in the main path and finally it is evaluated as grade 1. If a curve does not fulfill a criterion score it follows the arrow on the right where there are two different path options depending on the block:

- The curve follows the arrow on the right and finally is evaluated as grade 0
- The curve enters in one or more control boxes and if the score is above the threshold, the curve is evaluated as grade 2 and returns to the main path; otherwise the curve follows the arrow on the right and finally is evaluated as grade 0.

Each score (S_n) refers to the respective criterion (C_n) except the S_{13} (TOT SCORE) that is calculated as the sum of all the S_n of all the criteria (n): $S_{13} = \sum_n S_n$ and it is used in the final control.

Zone Z1 Analysis

The zone starts at the beginning of the spirometry test and ends once it has been determined that the peak exhalation flow PEF has occurred. The criteria ensure that the slope of the curve is regular and free from fluctuations and are based on the first and second derivative of the FV curve in the zone Z1. Table S1 lists the different threshold used for the comparison tests of the metrics.

The metric M_1 (*Diff2*) is defined as the second order derivative of the FV curve in Z1. The metric M_2 (*AreaDiff*) is defined as the sum of the negative values of the first order derivative of the curve. The metric M_3 (*AreaDiff2*) is defined as the sum of the positive values of the second order derivative of the FV curve.

A set of criteria have been developed to detect irregular concavity or convexity before the PEF value. In the criterion C_1 (*Diff_single*) it is determined that irregular concavity or convexity exists if the extracted signal metric has a second order derivative which exceeds the threshold of metric M_1 . In a second criterion C_{2a} (*Area Diff*) it is determined that the profile has an irregular slope if M_2 exceeds the 50 % of the sum of derivative values of zone Z1. In the criterion C_{2b} (*Area Diff2*) it is determined that the profile has an irregular concavity or convexity if the sum of the threshold of metric M_3 exceeds the sum of all derivative values of the zone Z1. Figure S1 depicts the flow-chart of the decision process in Z1.

TABLE S1

All the Z1 criteria associated with metrics and respective thresholds

<i>N</i>	CRITERION (C_n)	METRICS	MAIN THRESHOLD (th_n) <i>i=1</i>	VALUE
C1	Diff_single	M_1	<i>diff2Th</i>	0.1 L/s ²
C2a	Area Diff	M_2	<i>diffAreaTh</i>	50 % of the sum of all derivative values of the interval
C2b	Area Diff2	M_3	<i>diff2AreaTh</i>	100 % of the sum of all derivative values of the interval

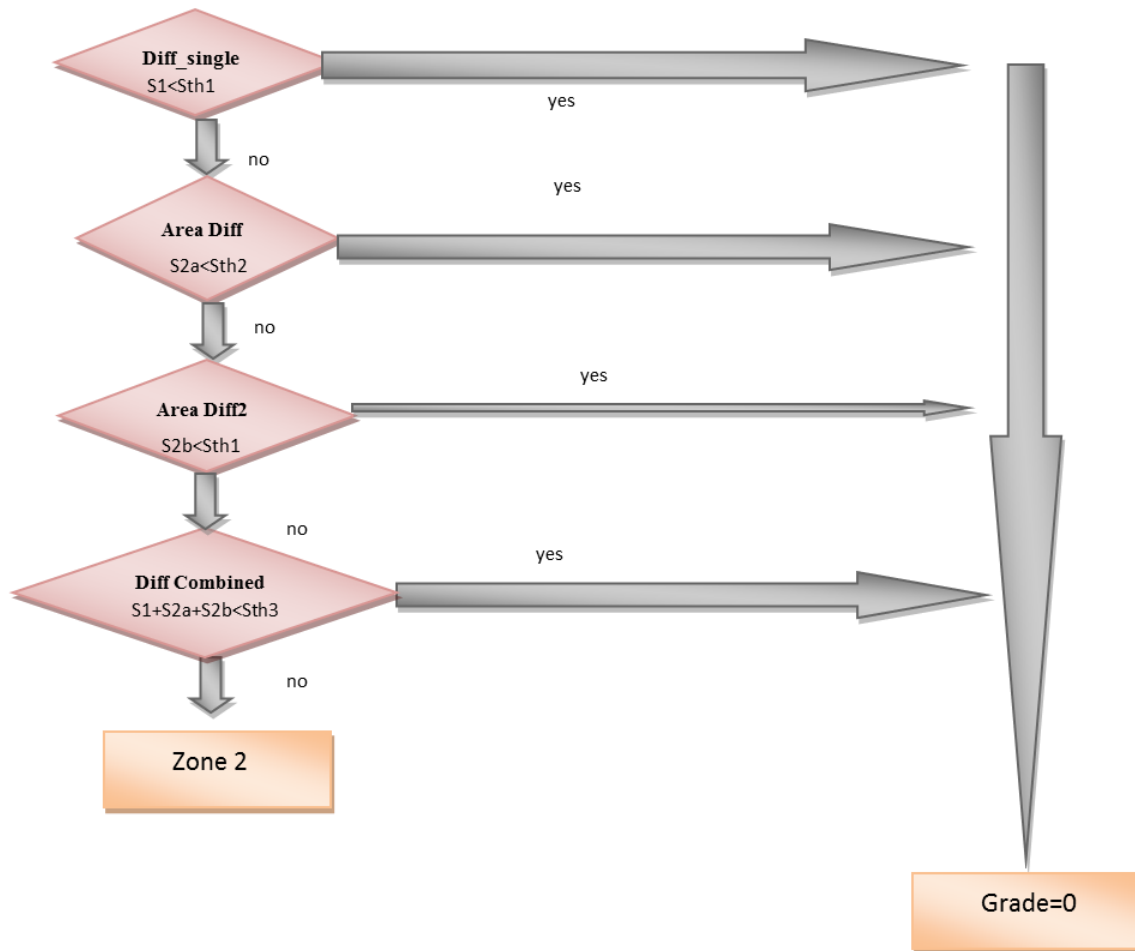


Figure S1 – Flowchart of the algorithm in Z1: in each decision box the curve scores (S_n) or the combination of scores are compared with the respective threshold (S_{thn}), the rectangular box are used to assign a grade to the curve or to go to the following zone.

Zone Z2 Analysis

This group of criteria has been developed to analyze the morphology of the maneuver around the *PEF* point in *VT*, *FT*, and *FV* profiles. The zone is centered about the *PEF* point. The criteria ensure that the *PEF* occurs at an early point in the maneuver, it has an appropriate height to width ratio and there are no secondary peaks present. Table S2 lists the different threshold used for the comparison tests of the metrics in each criterion.

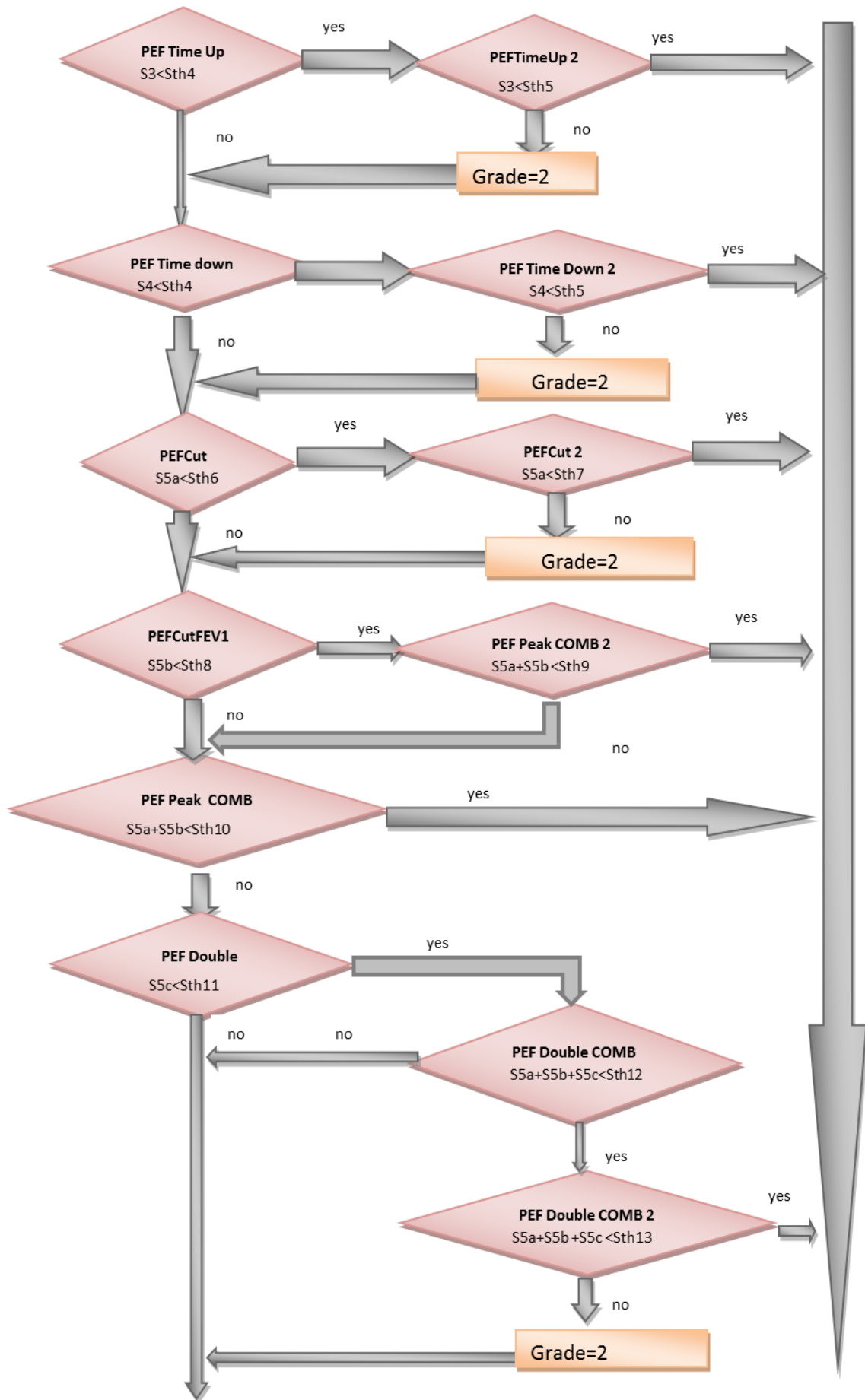
The metrics M_4 and M_5 are based on the intersection between the *FV* curve and a horizontal line, the height position of the horizontal line is M_4 , while the length is M_5 . These metrics ensure that *PEF* must be a peak in *FV* curve. Threshold of the peak is fixed relative to *FVC* (*PEF Peak*) or relative to *FEV1* (*PEF Peak2*). The metric M_6 (*PEFDouble*) aims to detect a “*PEF bimodal*” and corresponds to the difference between absolute maximum and consecutive relative maximum of *FV* curve. The metric M_7 is defined as the corresponding volume value at the *PEF* point. Traditional metrics *FEV1*, *FVC* and *PEFT* are also used. In criterion C_3 , it is determined that *PEF* point occurs too late if the corresponding time at the *PEF* occurrence is greater than a set threshold (*ThPEFup*). In criterion C_4 it is determined that the *PEF* point is too early if the corresponding time at which the *PEF* occurs is less than a set threshold (*ThPEFdown*). The criterion C_5 analyzes the peak. C_{5a} and C_{5b} detect a flat peak. The criterion

C_{5c} detects a situation of bimodal peaks (multiple peaks) when a secondary local maximum in the FV curve has F value higher than a fixed threshold percentage ($ThBIPEF$) of PEF. Figure S2 depicts the flow-chart of the decision process in Z2.

TABLE S2

All the Z2 criteria associated with metrics and respective thresholds

N	CRITERION (C_n)	METRICS	MAIN THRESHOLD (th_{ni}) $i=1$	VALUE	SECONDARY THRESHOLD (th_{ni}) $i=\{2,3\}$	VALUE
C3	PEF Time Up	PEFT	$ThPEFup$	0.12 s		
C4	PEFTimeDown	PEFT	$ThPEFdown$	0.25 ms		
C5a	PEF Peak1	M_4 and M_5	$ThOriz1$	15 % of FVC	$ThVert1$	10 of % PEF
C5b	PEF Peak2	M_4 and M_5	$ThOriz2$	17.5 % of FEV1	$ThVert2$	12.5 % of PEF
C5c	PEFDoubleTest	M_6	$ThBIPEF$	30 % of PEF		
C6	PEF Slow test	M_7	$ThPefSlow$	20 % of FVC		



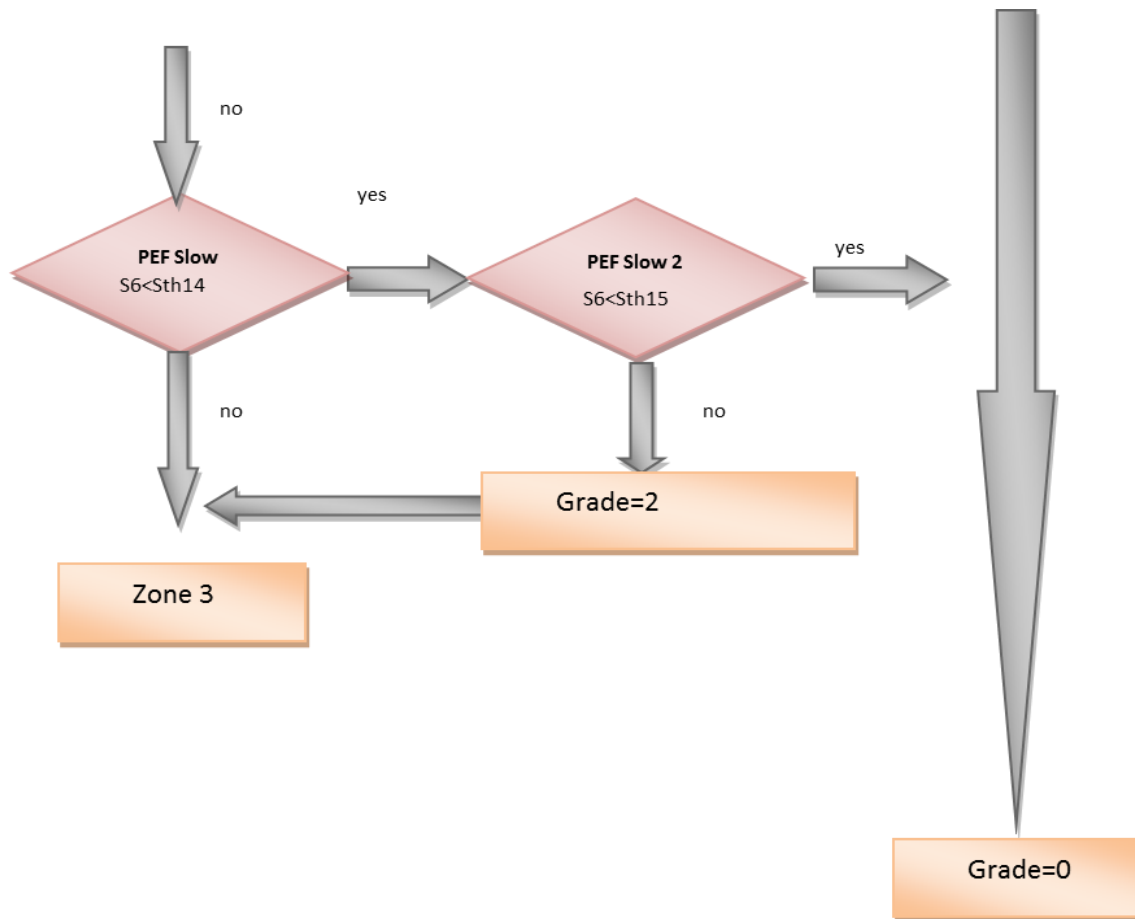


Figure S2 – Flowchart of the algorithm in Z2: in each decision box the curve scores (S_n) or the combination of scores are compared with the respective threshold (S_{thn}), the rectangular boxes are used to assign a grade to the curve or to go to the following zone.

Zone Z3 Analysis

This group of criteria has been developed to analyze the descent in the FV curve. The zone starts at the beginning of the PEF point and ends before the end of the FV curve. The criteria ensure that the slope of the curve is regular and free from fluctuations and are based on the first derivative, and definite integrals of the FV curve in the zone Z3. Table S3 lists the different threshold used for the comparison tests of the metrics.

The metric M_8 is defined as the first order derivative of the FV curve in Z3. The metric M_9 is defined as the area between FV curve and a line from the PEF to the point in which the magnitude of the first order derivative exceeds a predefined threshold. Traditional metrics PEF , $FEV1$ and FVC are also used.

The criterion C_{7a} detects a situation of high slopes during FV curve descent when the maximum value of the first order derivative of the FV curve exceeds a threshold percentage (Max_Slope) of PEF for volume values above a threshold percentage ($PosFVSI$) of FVC. The criterion C_{7b} detects an excessive variation in the slope of the FV curve in the zone Z3 when the first order derivative exceeds a threshold ($MaxSlope / KSlopeTest$) for subsequent values of V that occur after the point at which the first order derivative falls below a threshold percentage (Min_Slope) of PEF. The criterion C_{7c} detects an excessive variation in the slope calculated in a V segment of length $ThSlopeCalc$ of the FV curve in the zone Z3 when the first order derivative exceed a threshold ($ThDerivTest$) for subsequent values of V it cannot go up the threshold $ThSITest2$ % of PEF. The criterion C_{7d} detects an irregular slope by combining the previous M_8

and M_9 . Figure S3 depicts the flow-chart of the decision process in Z3.

TABLE S3

All the Z3 criteria associated with metrics and respective thresholds

n	CRITERION (C_n)	METRICS	MAIN THRESHOLD (th_{ni}) $i=1$	VALUE	SECONDARY THRESHOLD (th_{ni}) $i=\{2,3\}$	VALUE
C7a	FV_Max_Slope	M_8	<i>Max_Slope</i>	17.5 % of PEF	<i>PosFVSI</i>	40 % FVC
C7b	FV_Slope_test	M_8	<i>Max_Slope</i> <i>KSlopeTest</i>	16.75 % of PEF 2	<i>Min_Slope</i> <i>TSlope</i>	1.1 L/s 0.1 s
C7c	FVSlopeTest2	M_8	<i>ThSITest2</i>	20 % of PEF	<i>ThDerivTest</i> <i>ThSlopeCalc</i>	0.010 L/s ² 0.5 L
C7d	FVSlopeTestArea	M_8 and M_9	<i>ThFVSlopeTArea</i>	0.01 L		

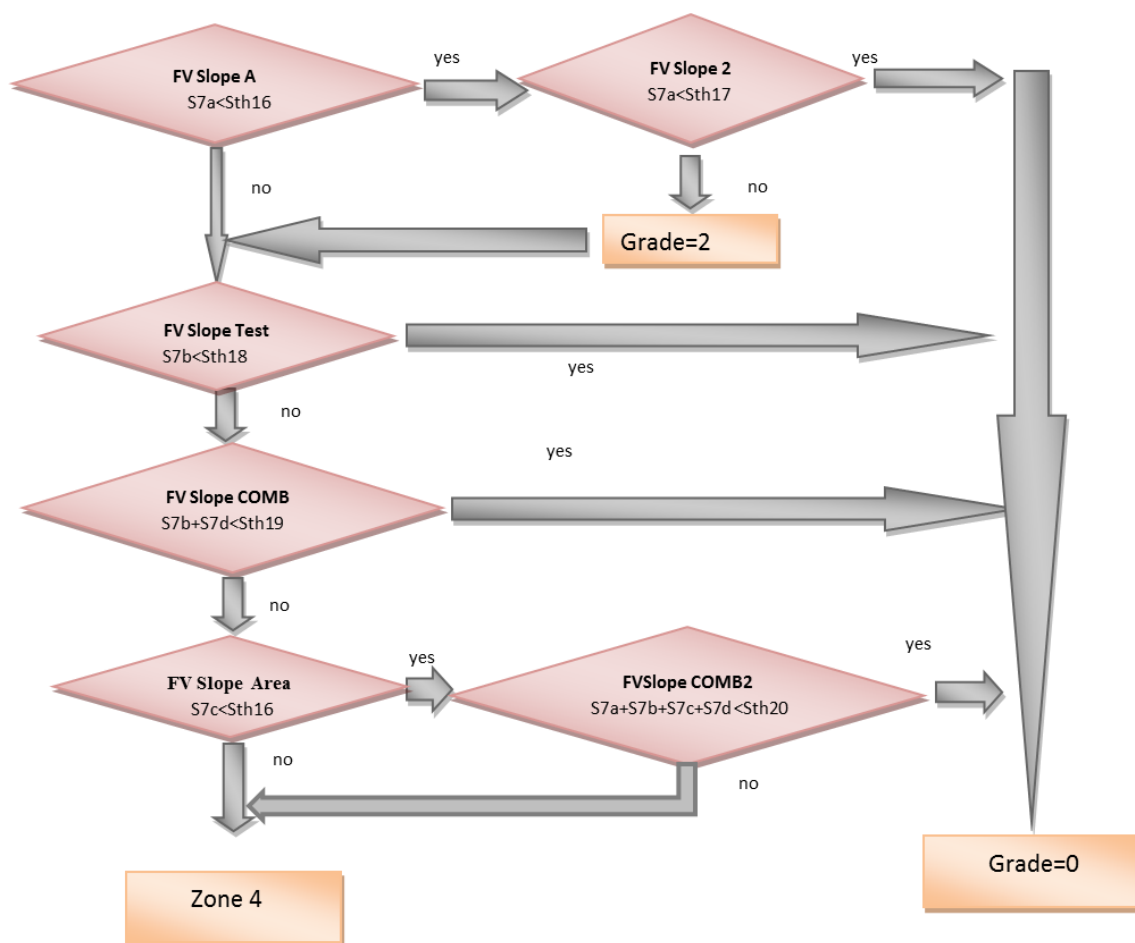


Figure S3 – Flowchart of the algorithm in Z3: in each decision box the curve scores (S_n) or the combination of scores are compared with the respective threshold (S_{thn}), the rectangular boxes are used to assign a grade to the curve or to go to the following zone.

Zone Z4 Analysis

This group of criteria has been developed to analyze the last two seconds of FV and VT

curves. The criteria ensure that the flow at the end of the curve is regular and free from fluctuations and are based on the first order derivative of FT curve in the zone Z4, and the difference between max and min volume in the last 1 s of exhalation. Table S4 lists the different threshold used for the comparison tests of the metrics.

A new metric M_{10} defines the $EOTV$ as a function of T_{ex} . The metric M_{11} defines a new threshold for $EOTV$ ($EOTV_{th}$) as a function of T_{ex} . A new metric M_{12} is calculated in the FT curve as the slope at the curve end. Besides, in the end of VT curve a horizontal line of 1 s of length is generated and the area under and above this line is calculated (M_{13}).

Criteria C_8 is the traditional BEV criteria ($BEV > 0.15$ L or $BEV < 5\%$ of FVC). Criteria C_9 is the traditional $EOTV$ criteria ($V < 0.025$ L in $t \geq 1$ s). Criteria C_{10} is a combination of 5 criteria based on the interaction between traditional $EOTV$ and T_{ex} and the metrics M_{10} and M_{11} . C_{10a} detects if the $EOTV$ and T_{ex} both does not satisfy their traditional criteria. C_{10b} defines a new period to calculate $EOTV$ if the T_{ex} traditional criteria is satisfied. C_{10c} defines a new threshold for $EOTV$ if the T_{ex} traditional criterion is satisfied. C_{10d} uses threshold M_{10} to define the $EOTV(T_{ex})$ and compare with the traditional threshold. C_{10e} defines a new threshold for $EOTV$ (M_{11}) calculated as a function of T_{ex} . Criterion C_{11} detects irregularity or oscillation at the end part of FT curve when the FT curve exceeds a threshold (FT_{endMx}) for subsequent values of F that occur after the point at which the first order derivative falls below a threshold (FT_{endMin}) of PEF. This value is combined with the value (M_{13}) of the area generated by a horizontal line of 1 s in the end of VT curve. Figure S4 depicts the flow-chart of the decision process in Z4.

TABLE S4

All the Z4 criteria associated with metrics and respective thresholds

n	CRITERION (C_i)	METRICS	MAIN THRESHOLD (th_m) $i=1$	VALUE	SECONDARY	
					THRESHOLD (th_m) $i=\{2,3\}$	VALUE
C8	BEV	BEV	BEV_{th}	0.150 L		
C9	EOTVtrad	EOTV	$EOTV_{th}$	0.025 L		
C10a	EOTV_Tex	EOTV and T_{ex}	T_{maxEx}	6 s		
C10b	EOTV_Tex_05s	EOTV and T_{ex}	$EOTV_{th}$	0.025 L	$TEotv$	0.5 s
C10c	EOTV_Tex_Th01	EOTV and T_{ex}	$EOTV_{th2}$	0.050 L		
C10d	EOTV(Texp)	M_{10}	$EOTV_{th}$	0.025 L		
C10e	EOTV_Tex_ThVar	M_{11}	$EOTV_{thDyn}$	$EOTV_{th}(T_{ex}) = EOTV_{th} \frac{T_{ex}}{6}$		
C11	FT_end	M_{12} and M_{13}	FT_{endMx} $AuVTh$	5 % of PEF 0.025 L	FT_{endMin}	0.00001 L/s

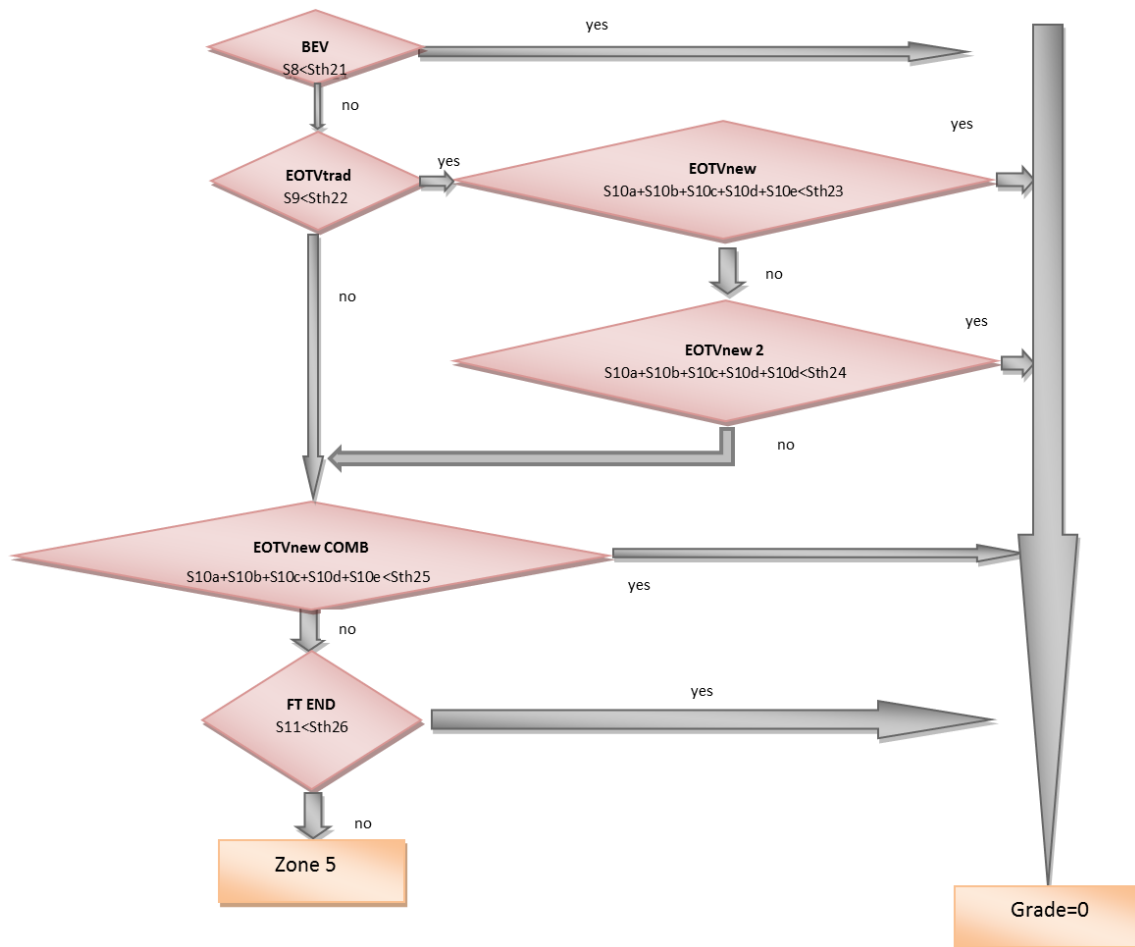


Figure S4 – Flowchart of the algorithm in Z4: in each decision box the curve scores (S_n) or the combination of scores are compared with the respective threshold (S_{thn}), the rectangular boxes are used to assign a grade to the curve or to go to the following zone.

Zone Z5 Analysis

This group of criteria has been developed to analyze the morphology of the entire FV curve. The criteria ensure that there only exists one local maximum (the *PEF* point) and they are based on the derivative of the FV curve. Table S5 lists the different threshold used for the comparison tests of the metrics.

The metric M_{14} is defined as the maximum of the difference between all local minimum and consecutive local maximum on the FV curve detected by analyze the sign of the first order derivative of the FV curve.

The criterion C_{12a} detects a situation of multiple peaks when the M_{14} exceeds a certain percentage threshold ($PVFVThI$) of the *PEF* that typically occurs when the subject coughs. The criterion C_{12b} detects a situation of multiple peaks for values of V adjacent to *FEV1* when the height of secondary local maxima exceeds a threshold function of the distance to *FEV1* ($PVFVThDyn$). Figure S5 depicts the flow-chart of the decision process in Z5.

TABLE S5

All the Z5 criteria associated with metrics and respective thresholds

N	CRITERION (C_n)	METRICS	MAIN THRESHOLD (th_{ni}) $i=1$	VALUE
C12a	Peak_Valley_Single	M_{14}	$PVFVTh1$	5 % of PEF
C12b	Peak_Valley_Combined	M_{14}	$PVFVThDyn = dFEV1$ $PVFVTh1$	$PVFVTh1 = 2.5$ % of PEF $dFEV1 = 100 * \frac{ F_{pv} - F_{FEV1} }{FVC}$

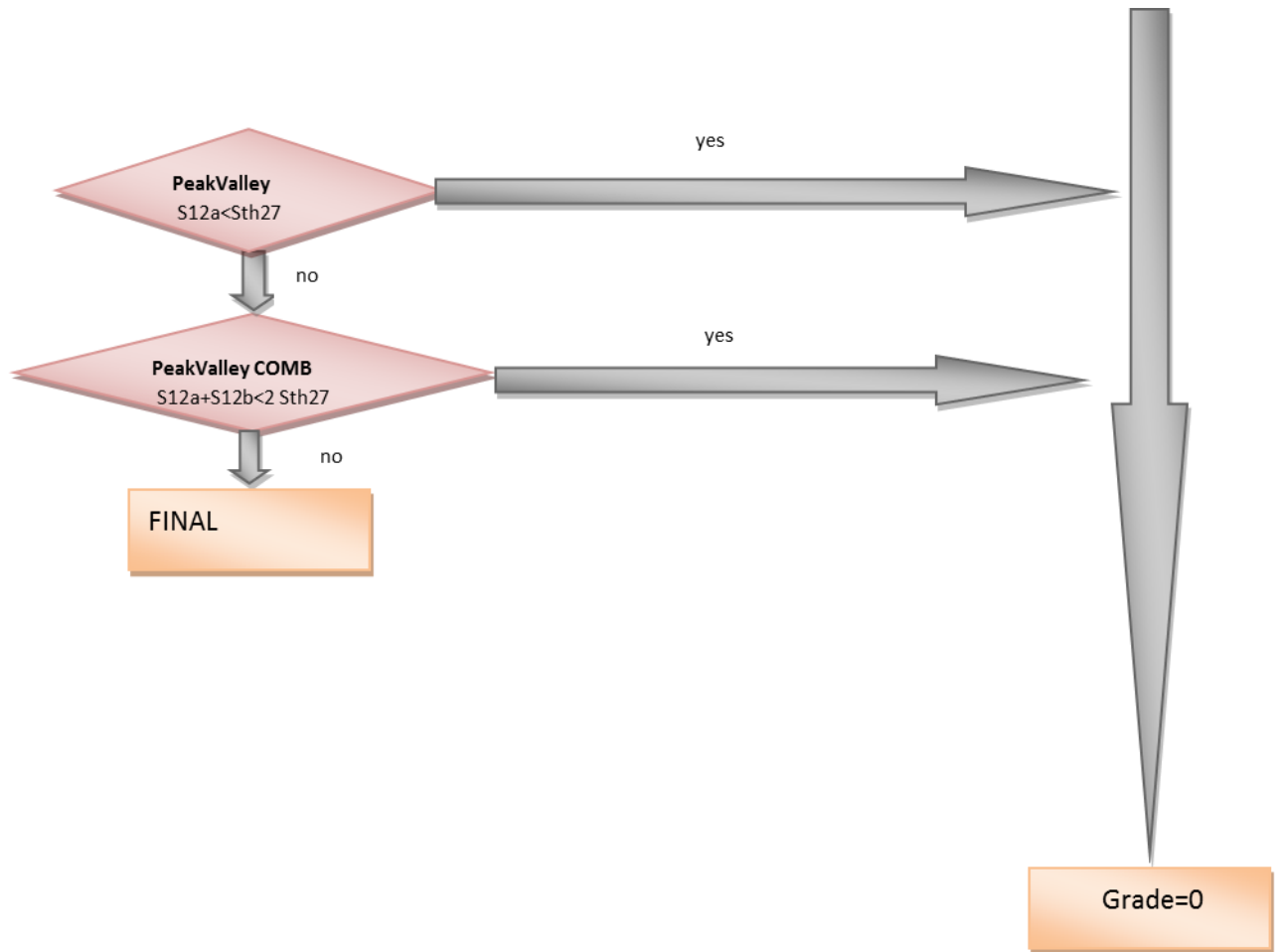
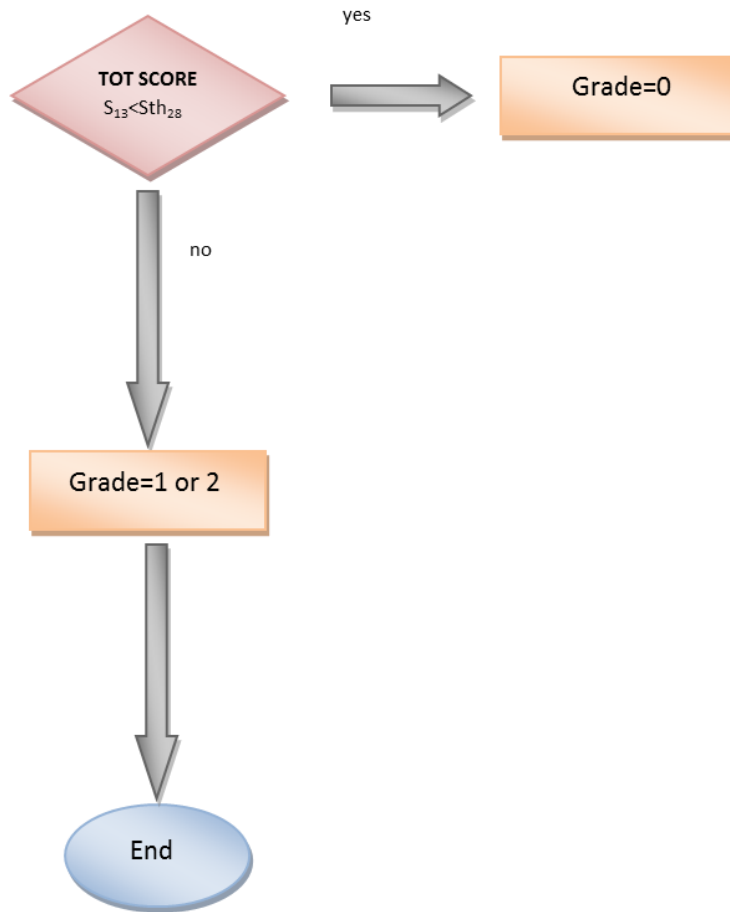


Figure S5 – Flowchart of the algorithm in Z5: in each decision box the curve scores (S_n) or the combination of scores are compared with the respective threshold (S_{thn}), the rectangular box are used to assign a grade to the curve or to go to the following zone.

The Final Control

The final control (Figure S6) is based on S_{13} (TOT SCORE) that is calculated as the sum of all the S_n of all the criteria (n): $S_{13} = \sum_n S_n$.



(f)

Figure S6 – Flowchart of the algorithm of the Final control.

Table S6 contains a list of all the score thresholds associated with the criteria.

TABLE S6

All the score threshold values of each block

CODE	CRITERIA	BLOCK	SCORE THRESHOLD (Sth_n)
Sth 1	C ₁ and C _{2b}	Diff_single/Area Diff2	50
Sth 2	C _{2a}	AreaDiff	100
Sth 3	C ₁ , C _{2a} and C _{2b}	Diff Combined	250
Sth 4	C ₃ and C ₄	PEF Time Up/Down	50
Sth 5	C ₃ and C ₄	PEF Time UP/Down 2	75
Sth 6	C _{5a}	PEF Cut	50
Sth 7	C _{5a}	PEF Cut 2	75
Sth 8	C _{5b}	PEF Cut FEV1	50
Sth 9	C _{5a} and C _{5b}	PEF Peak COMB 2	75
Sth 10	C _{5a} and C _{5b}	PEF Peak COMB	100
Sth 11	C _{5c}	PEF Double	50
Sth 12	C _{5a} , C _{5b} and C _{5c}	PEF Double COMB	150
Sth 13	C _{5a} , C _{5b} and C _{5c}	PEF Double COMB 2	125
Sth 14	C ₆	PEF Slow	50
Sth 15	C ₆	PEF Slow 2	75
Sth 16	C _{7a} and C _{7c}	FV Slope / FV Slope	40
Sth 17	C _{7a}	FV Slope 2	75
Sth 18	C _{7b}	FVSlope Test	50
Sth 19	C _{7b} and C _{7d}	FVSlope COMB	175
Sth 20	C _{7a} , C _{7b} , C _{7c} and C _{7d}	FVSlope_COMB 2	160
Sth 21	C ₈	BEV	100
Sth 22	C ₉	EotvTrad	100
Sth 23	C _{10a} , C _{10b} , C _{10c} , C _{10d} , C _{10e}	EOTVnew	350
Sth 24	C _{10a} , C _{10b} , C _{10c} , C _{10d} , C _{10e}	EOTVnew 2	400
Sth 25	C _{10a} , C _{10b} , C _{10c} , C _{10d} , C _{10e}	EOTV new COMB	360
Sth 26	C ₁₁	FTend	40
Sth 27	C _{12a} and C _{12b}	Peak_Valley/PeakValley	50
Sth 28	C ₁ -C _{12b}	TOT SCORE	1350