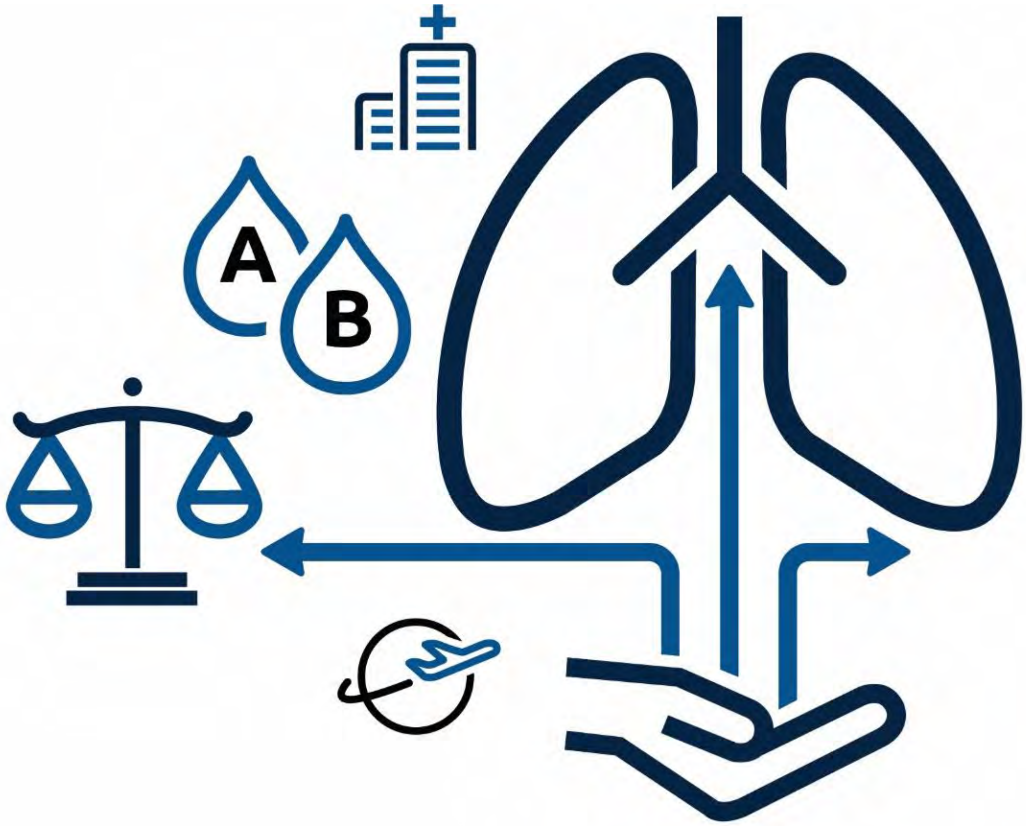


A guide to calculating the

Lung Composite Allocation Score (Lung CAS)

OPTN Organ Procurement & Transplantation Network

Updated September 12, 2023

Background

Effective in early 2023, the lung allocation policy is based on the continuous distribution framework. Continuous distribution uses a composite allocation score to determine the preferential order of candidates on a match run[1] when a medically suitable lung donor becomes available.

This point-based system replaced the previous, classification-based system. Under the classification-based system, candidates were first arranged into ordered groups (e.g., "blood type identical, within 250 nautical miles of the donor hospital") and then, within each group, preferentially ordered by Lung Allocation Score (LAS).

In contrast, continuous distribution does not use candidate groupings. Instead, all candidates are prioritized using a composite allocation score that takes into account medical, biological, and other factors permitted by the Final Rule to determine preferential ordering on a match run. Though lung candidates no longer receive a LAS, the composite score essentially includes the two components of the LAS: a waiting list urgency measure (WLAUC) and a post-transplant survival measure (PTAUC; based on predicted 5-year, instead of 1-year, survival).

Attributes included in the Lung Composite Allocation Score (Lung CAS)

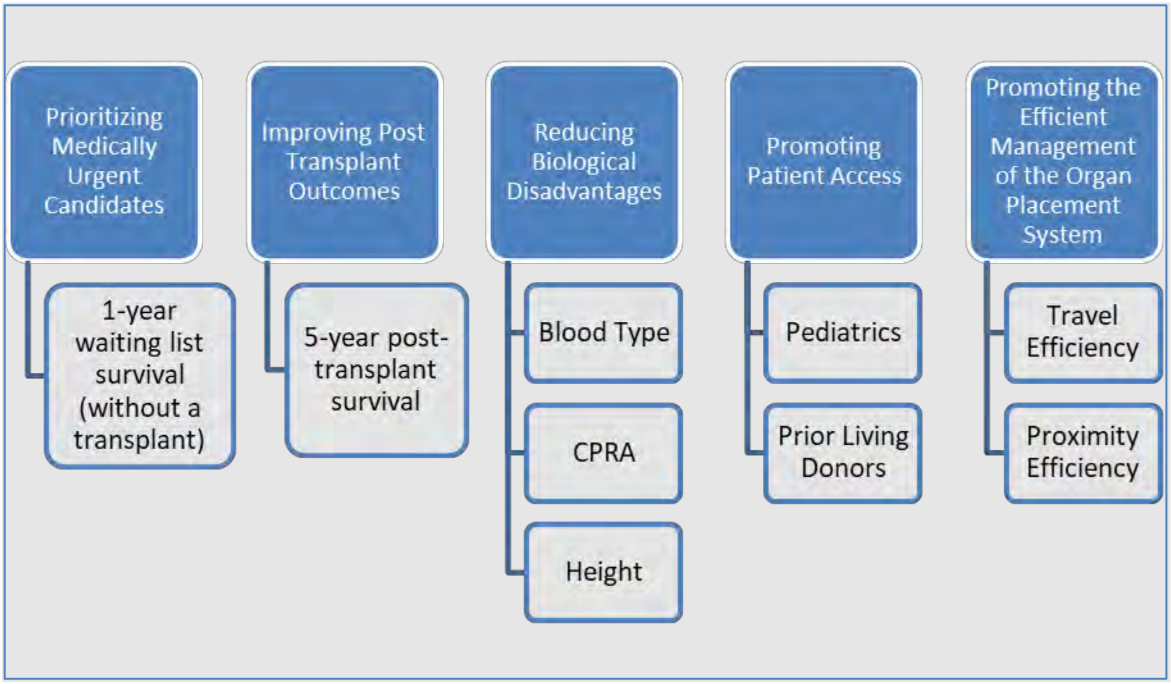
The Lung CAS incorporates the following nine candidate attributes:

- Expected 1-year waiting list mortality (without a transplant) (WLAUC)
- Expected 5-year post-transplant survival (PTAUC)
- Blood type
- CPRA (measure of HLA antibody sensitization)
- Height
- Pediatric status (less than 18 years old at the time of registration)
- Prior living donor status
- Travel efficiency (travel and transportation costs)
- Proximity efficiency (other inefficiencies related to distance between organ recovery and transplant hospitals)

Each attribute aligns with one of the five allocation policy goals, as shown in Figure 1.

[1] A "match run" is an ordered list of transplant candidates who are medically eligible for an organ from a particular donor. Organ Procurement Organizations (OPOs) use these ordered lists to allocate organs. The candidate ranked first on the match run receives first opportunity to accept the organ; if the offer is declined on behalf of the patient, the second ranked candidate is given a chance to accept the transplant, and so on.

Figure 1. Allocation Policy Goals and Candidate Attributes



Understanding Attribute Weights

Attribute weights reflect the relative importance placed on each attribute in the Lung CAS. The weights can be thought of as percentages, reflecting the relative contribution of each attribute to the score. However, instead of summing to 100%, the weights are integers that sum to 100, such that the composite score maintains the familiar 0 to 100 scale.

Table 1 shows the attribute weights used to calculate the Lung CAS. The pediatric attribute for example has a weight of 20, revealing the lung allocation policy places a high value on providing transplant access to candidates listed prior to their 18^{th} birthday.

These weights were derived through extensive transplant community input, OPTN Lung Committee deliberations, simulation modeling, and mathematical optimization to determine a policy that best serves lung transplant candidates in a manner aligned with the Final Rule.

Table 1. Lung Composite Allocation Score Attribute Weights

Attribute	Attribute Weight
Waitlist survival (W_{WLAUC})	25
Post-transplant Survival (W_{PTAUC})	25
ABO (W_{ABO})	5
CPRA (W_{CPRA})	5
Height (W_{HGT})	5
Pediatric (W_{PED})	20
Prior Living Donor (W_{PLD})	5
Proximity Efficiency (W_{EFF})	5
Travel Efficiency (W_{COST})	5
Total	100

Understanding Rating Scales

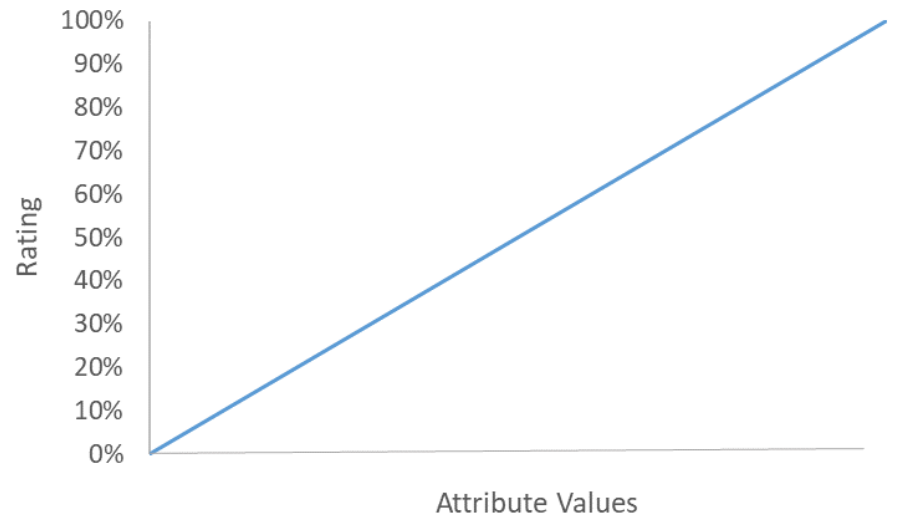
Each attribute, or candidate characteristic, can take on different values. For example, the blood type attribute has four different values: A, B, AB, and O. By comparison, the proximity efficiency attribute reflects the distance between the donor and transplant hospitals and can take on values between 0 and 5,200 nautical miles. Every lung candidate on a match run has a value for each of the nine Lung CAS attributes.

Rating scales assign all possible values of an attribute to a number ranging between 0 and 100%. Attribute values assigned higher ratings improve a candidate's priority in lung allocation, and vice versa, consistent with allocation policy goals. Converting attribute values to ratings using a consistent scale allows for attributes of various types (for example, blood types and distances) to be combined into a single, composite allocation score.

Rating scales can take on varying shapes, determined by data analysis or value judgements. For example, Figure 2 shows a linear, increasing rating scale. For an attribute with a linear, increasing rating scale:

- Higher values of the attribute receive more allocation points
- Differences in attribute values are treated equally across the spectrum of possible attribute values

Figure 2. Linear, Increasing Rating Scale



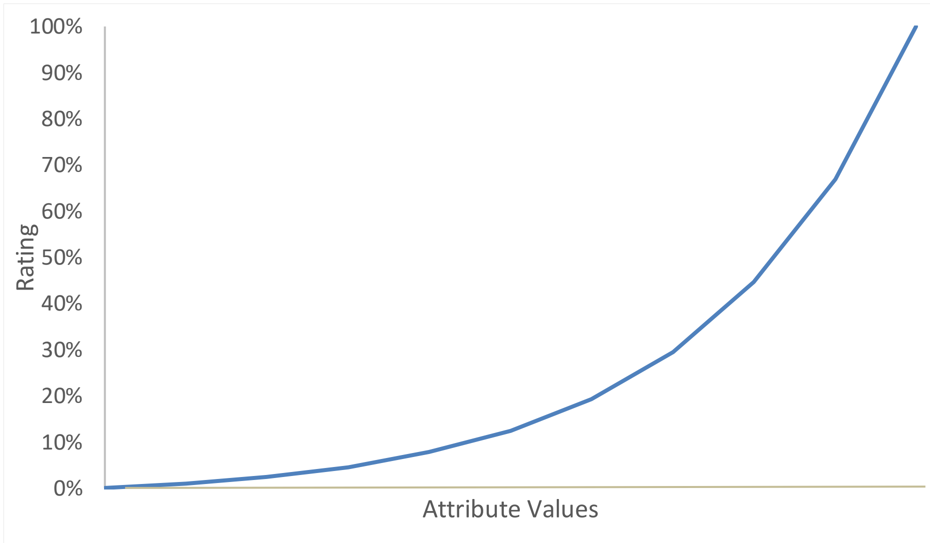
By contrast, a linear, *decreasing* rating scale would have these characteristics:

- *Lower* values of the attribute receive more allocation points
- Differences in attribute values are treated equally across the spectrum of possible attribute values

Though linear rating scales are easier to understand and interpret, sometimes nonlinear rating scales are needed to accomplish policy goals. Figure 3 shows a nonlinear, increasing rating scale with these features:

- Higher values of the attribute receive more allocation points
- Differences in attribute values at the *high end* of the value range lead to a greater difference in allocation points than differences at the *low end*.

Figure 3. Nonlinear, Increasing Rating Scale



Nonlinear rating scales can have many different features, such as

- Increasing vs. decreasing
- Degrees of nonlinearity (e.g., highly nonlinear vs. only slightly different from a straight line)
- Convex vs. concave
- Monotonic vs. non-monotonic

The example rating scales shown above apply to numeric attribute values, for example distances and estimated days of post-transplant survival. However, rating scales are also used with these types of attributes:

- Binary (e.g., pediatric status: yes or no)
- Categorical (e.g., blood types)

For binary and categorical attributes, rating scales still range between 0 and 100%. If a candidate has that attribute, they receive 100% of the points for it, and if they do not, they do not receive any points for that attribute.

One approach to creating the composite score would be to simply add together a candidate's ratings for each of the nine attributes to derive his or her score. However, this approach would assume each attribute is equally important, which is not the case.

Instead, the Lung CAS is calculated by using *attribute ratings* together with *attribute weights*, which reflect different levels of importance placed on each component of the score.

Calculating the Lung CAS

A candidate's Lung CAS is computed using these steps.

1. Collect the candidate's attributes
2. Determine the candidate's attribute ratings for each of the nine attributes
3. Multiply each attribute rating by the associated attribute weight in Table 1
4. Add all nine products from step 3 together

The Lung CAS calculation is expressed mathematically as follows:

Lung CAS = (W_{WLAUC} x R_{WLAUC} + W_{PTAUC} x R_{PTAUC} + W_{ABO} x R_{ABO} + W_{CPRA} x R_{CPRA} + W_{HGT} x R_{HGT} + W_{PED} x R_{PED} + W_{PLD} x R_{PLD} + W_{EFF} x R_{EFF} + W_{COST} x R_{COST})

In this formula, the W's reflect the attribute weights shown in Table 1, and the R's reflect the attribute ratings derived from the rating scales.

Candidates are prioritized by descending Lung CAS; in other words, higher scores receive preferential allocation priority. The candidate with the highest score will appear first on the match run; the second-highest scoring candidate will appear second, and so on.

Rating Scales

Medical Urgency Rating Scale (WLAUC)

The medical urgency rating is a nonlinear function of the patient's expected days of survival (within a year) without a transplant, or WLAUC[2]. A patient predicted to survive close to a full year (365 days) without a transplant would receive a rating of nearly 0% for this attribute. By contrast, a patient expected to survive only a few days without a transplant would receive a rating close to 100%.

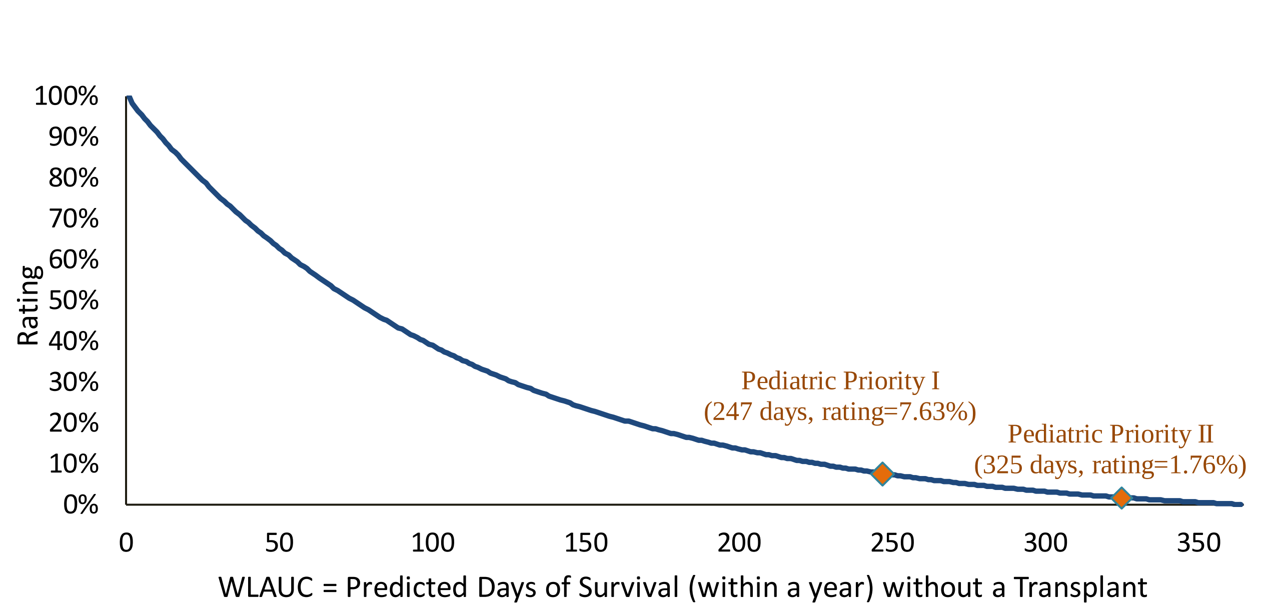
The medical urgency rating is determined by this formula

$$\text{Rating} = (25^{(1\text{-WLAUC}/365)} - 1)/24$$

The shape of this function is shown below in Figure 4. The nonlinear function – instead of a straight line – was chosen so that differences in patient ratings are magnified for the most medically urgent candidates, who may not be able to wait much longer for another lung offer due to high mortality risk.

[2] "WLAUC" refers to the waiting list "area under the curve," and is derived from the area under the estimated 1-year survival curve for each patient. This area provides an estimate of the average number of days a patient is expected to live up to the next year on the waitlist without a transplant, based on the person's diagnosis. It does not predict total time any patient may survive, which may be longer than one year. See the Appendix for more details about calculating WLAUC.

Figure 4. Medical Urgency Rating Scale



For candidates aged[3] less than 12, the medical urgency rating is based on their medical urgency status, priority I or II. As shown in Figure 4, Priority I candidates are estimated to have 247 days of survival without a transplant[4] and receive a rating of 7.63%. Priority II candidates are estimated to have 325 days of survival without a transplant4and receive a rating of 1.76%. See Appendix 1 for a detailed explanation of how to calculate WLAUC.

Post-transplant Survival Rating Scale (PTAUC)

The post-transplant survival rating is a linear function of the patient's predicted days of survival (within 5 years) with a transplant, or PTAUC[5]. A patient predicted to survive close to the full 5 years after a transplant would receive a rating of nearly 100% for this attribute. By contrast, a patient predicted to survive only a short amount of time after a transplant would receive only a small percentage of the rating.

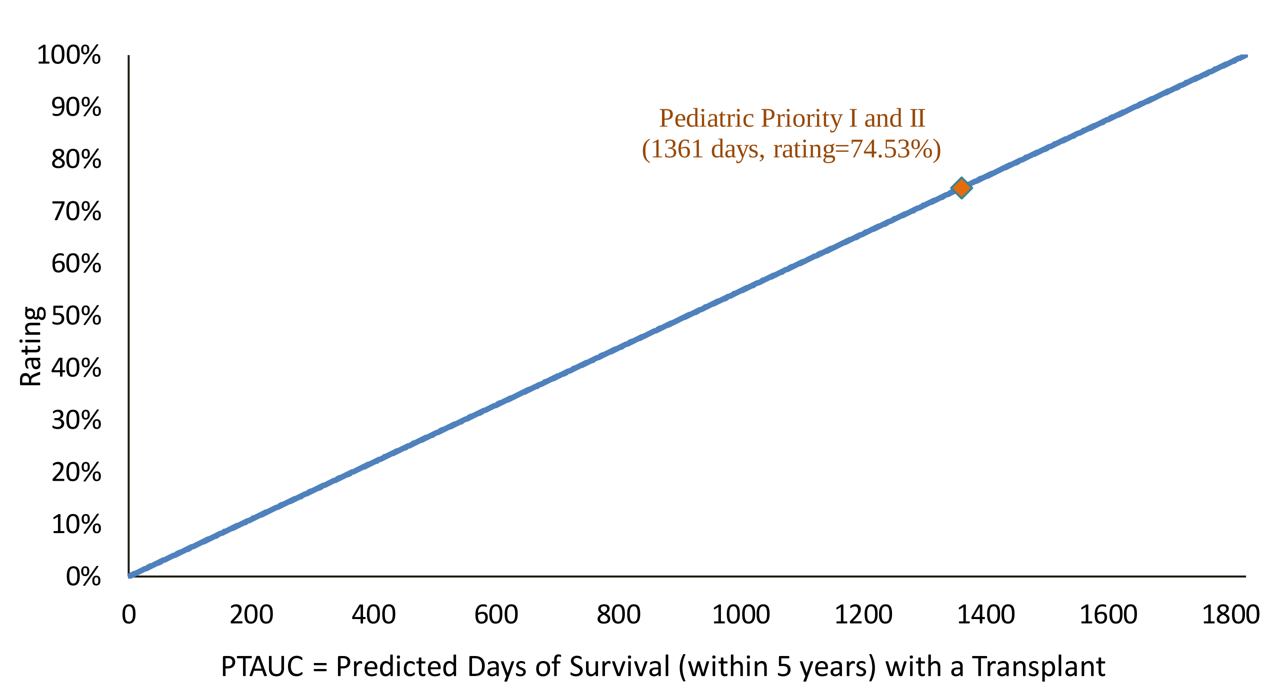
The post-transplant survival rating is determined by this formula

$$\text{Rating} = \text{PTAUC}/1826$$

The shape of this function (a straight line) is shown below in Figure 5.

[3] Based on age at time of match run.
[4] Based on SRTR analysis presented to the OPTN Lung Transplantation Committee during policy development.
[5] "PTAUC" refers to the post-transplant "area under the curve," and is derived from the area under the estimated 5-year survival curve for each patient. This area provides an estimate of the average number of days a patient is expected to live up to 5 years (1826 days) after a transplant, based on the person's diagnosis. It does not predict total post-transplant survival time for any patient, which may be longer than five years. See the Appendix for more details about calculating PTAUC.

Figure 5. Post-transplant Survival Rating Scale



For candidates aged[6] less than 12, the post-transplant survival rating is 74.53%, based on an estimated post-transplant survival of 1361 days[7]. This estimate did not differ statistically for Priority I and II recipients, so pediatric candidates less than 12 years old receive the same post-transplant survival score irrespective of medical urgency status. See Appendix 1 for a detailed explanation of how to calculate PTAUC.

Candidate Biology Rating Scales

The three candidate biology rating scales are all based on the proportion of donors with which a candidate is estimated to be biologically incompatible. The proportion of donors estimated to be biologically incompatible is mapped onto nonlinear rating scales.

Nonlinear rating scales were chosen because of the highly nonlinear relationship between proportion of donors estimated to be incompatible and access to transplant. This highly nonlinear relationship is illustrated as follows:

- Proportion incompatible = 0.5 → compatible with 1 in 2 donors
- Proportion incompatible = 0.9 → compatible with 1 in 10 donors
- Proportion incompatible = 0.99 → compatible with 1 in 100 donors
- Proportion incompatible = 0.999 → compatible with 1 in 1000 donors

[6] Based on age at time of match run.
[7] Based on SRTR analysis presented to the OPTN Lung Transplantation Committee during policy development.

This nonlinear relationship magnifies differences at the upper end of the incompatibility scale and minimizes differences at the lower end.

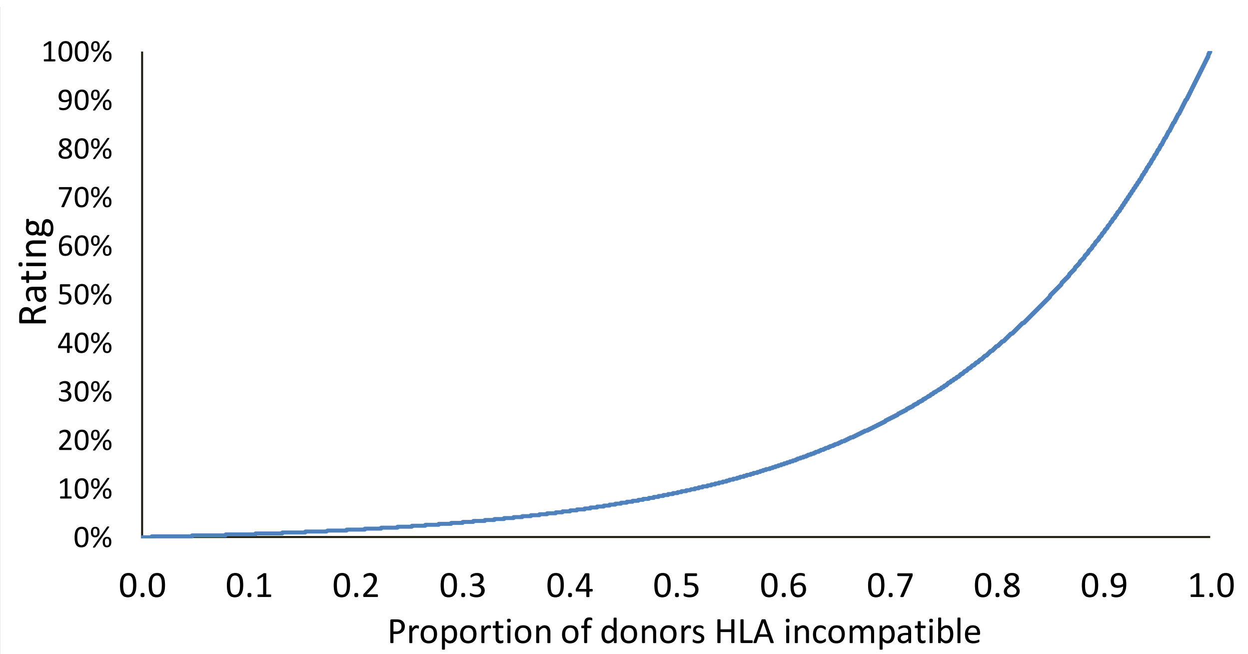
Sensitization (CPRA) Rating Scale

Calculated panel reactive antibodies (CPRA) directly estimates the proportion of donors with which a HLA-sensitized candidate is HLA incompatible.[8]

The candidate CPRA rating scale is expressed mathematically as follows:

$$\text{Rating} = (100^{(\text{CPRA})} - 1)/99$$

Figure 6. CPRA Rating Scale



Height Rating Scales

In order to accept a lung transplant, the candidate must be size-compatible with the donor. More specifically, the chest cavity size of the recipient must be compatible with the size of the donated lungs. Candidate height is associated with chest cavity size, and donor height is associated with size of the lungs[9]. In this way, the difference between donor and candidate heights serves as a proxy to

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[8] https://optn.transplant.hrsa.gov/resources/allocation-calculators/cpra-calculator/

[9] Keeshan BC, Rossano JW, Beck N, Hammond R, Kreindler J, Spray TL, Fuller S, Goldfarb S., Lung transplant waitlist mortality: height as a predictor of poor outcomes, Pediatr Transplant. 2015 May; 19(3):294-300. doi: 10.1111/petr.12390. Epub 2014 Nov 19. PMID: 25406495. Sell JL, Bacchetta M, Goldfarb SB, Park H, Heffernan PV, Robbins HA, Shah L, Raza K, D'Ovidio F, Sonett JR, Arcasoy SM, Lederer DJ. Short Stature and Access to Lung Transplantation in the United

determine whether a particular lung donor is likely to be size compatible with a particular candidate.

Analyses conducted on behalf of the OPTN Lung Committee revealed that lung donor and lung transplant recipient heights tend to be within +/- 20cm under current practice, but that this range differs slightly by candidate diagnosis group.

The candidate height rating scale is expressed mathematically as follows:

$$\text{Rating} = (100^{(\text{proportion height incompatible})} - 1)/99$$

Figure 7. Height Rating Scale

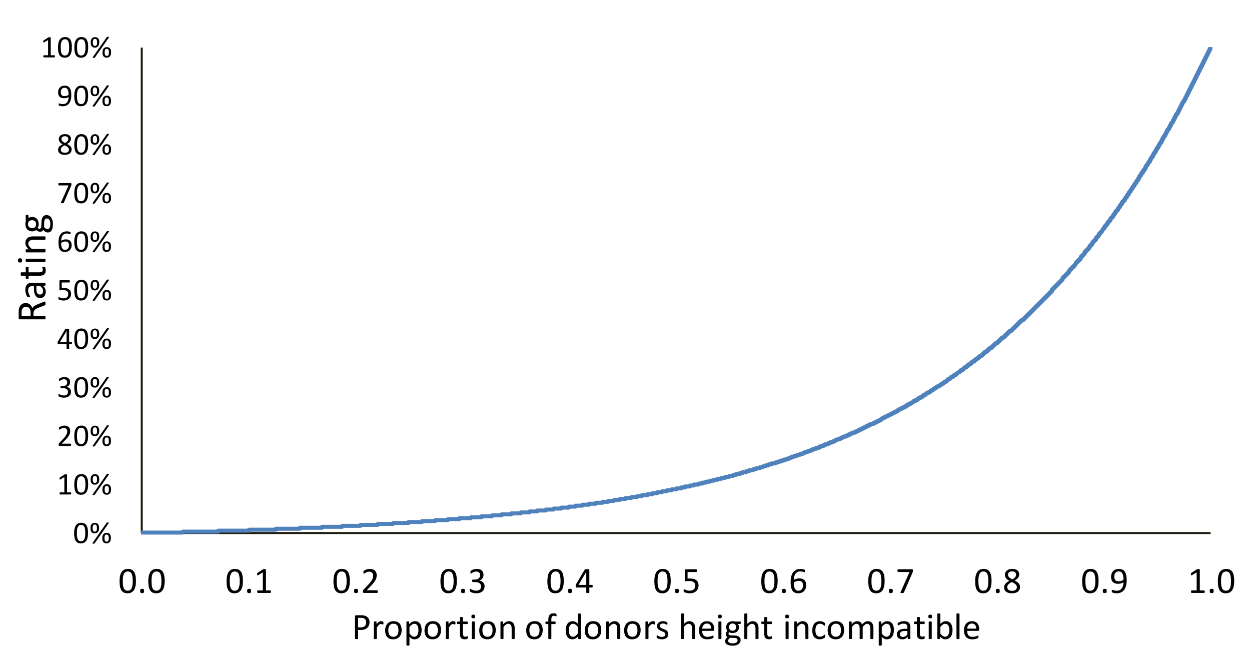
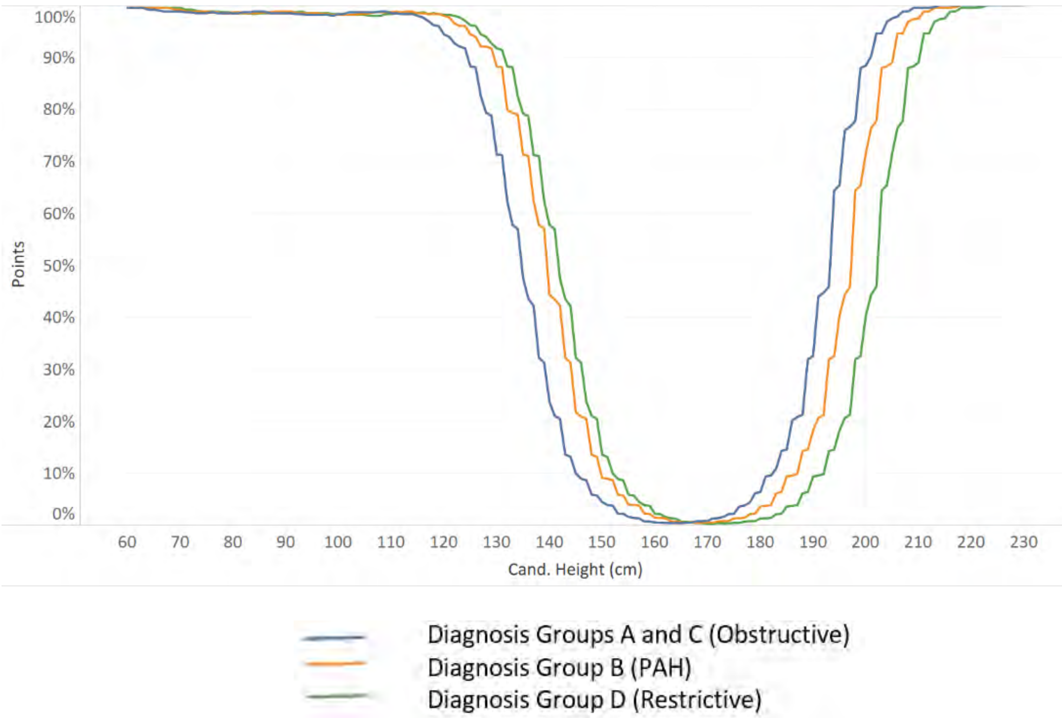


Figure 8 shows the proportion of donors estimated to be height-incompatible by candidate height and candidate diagnosis group.

States. A Cohort Study. Am J Respir Crit Care Med. 2016 Mar 15; 193(6):681-8. doi: 10.1164/rccm.201507-1279OC. PMID: 26554631; PMCID: PMC5440846. Weill D. Access to Lung Transplantation. The Long and Short of It. Am J Respir Crit Care Med. 2016 Mar 15; 193(6):605-6. doi: 10.1164/rccm.201511-2257ED. PMID: 26977969.

Figure 8. Proportion of Donors Estimated to be Height-Incompatible by Candidate Height and Candidate Diagnosis Group



The proportions illustrated in Figure 8 above are also provided in OPTN Policy Table 21-9 Proportion of Incompatible Donors Based on Lung Height.

A lung candidate's height attribute rating is calculated in two steps:

1. Looking up the incompatibility proportion in OPTN Policy Table 21-9 Proportion of Incompatible Donors Based on Lung Height.
2. Converting the proportion to the rating using the nonlinear candidate biology rating function: rating = $(100^{(\text{proportion height incompatible})} - 1)/99$

Blood Type Rating Scale

Candidates are blood type compatible with donors as follows:

- Type O candidates: compatible with Type O donors
- Type A candidates: compatible with Type A, O donors
- Type B candidates: compatible with Type B, O donors
- Type AB candidates: compatible with Type A, B, O, and AB donors

Based on lung donors recovered in 2019, the proportion of donors that are blood type compatible with each of the four candidate blood types is shown in Table 2.

Table 2. The Estimated Proportion of Blood Type Compatible and Incompatible Donors by Candidate Blood Type

Candidate Blood Type	Blood type-compatible donors	Proportion compatible*	Proportion incompatible*	Normalized proportion incompatible*	Rating
O	1375	0.49982	0.50018	1.00000	100.000%
A	2367	0.86041	0.13959	0.27907	6.064%
B	1698	0.61723	0.38277	0.76526	44.764%
AB	2751	1.00000	0.00000	0.00000	0.000%

* Proportion of donors compatible/incompatible with each candidate blood type are rounded to 5 decimal places in this table; however, values were not rounded when calculating the rating scale for the purposes of allocation.

The rating scale for blood type is scaled so that the blood type with the highest proportion of incompatible donors (blood type O) receive a rating of 100%. To do this, the normalized proportion of incompatible donors was calculated using the following equation:

Normalized proportion incompatible = proportion incompatible/range of blood type incompatibility

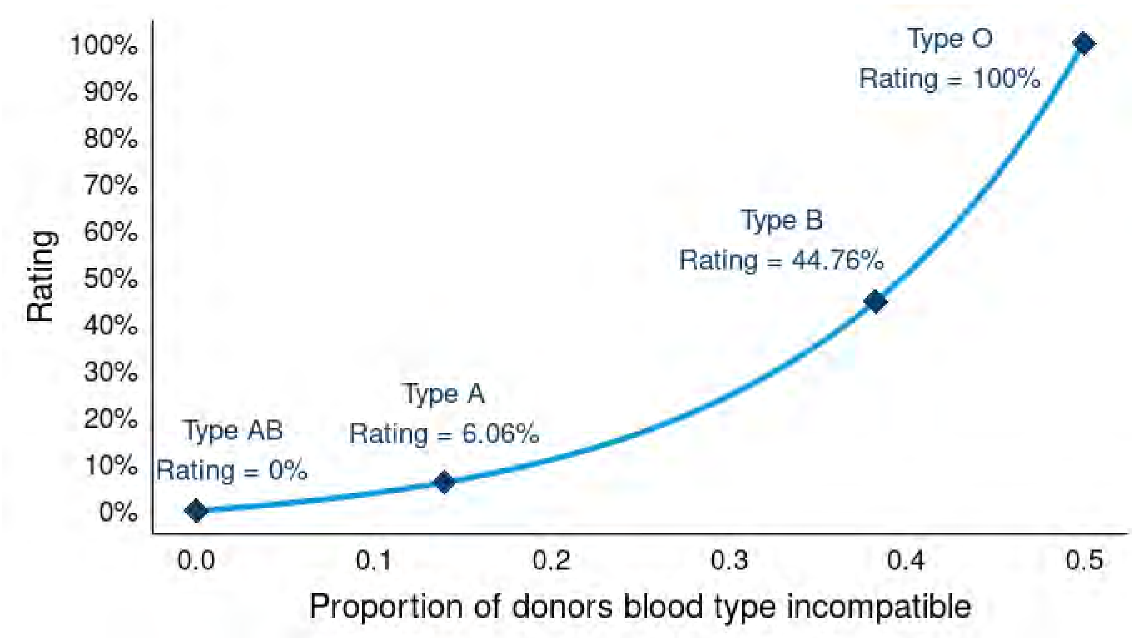
Normalized proportion of donors incompatible by blood type:

- Blood type O: 0.50018/(0.50018-0.00000) = 1.00000
- Blood type A: 0.13959/(0.50018-0.00000) = 0.27907
- Blood type B: 0.38277/(0.50018-0.00000) = 0.76526
- Blood type AB: 0.00000/(0.50018-0.00000) = 0.00000

The candidate blood type rating scale is expressed mathematically as follows:

$$\text{Rating} = (25^{(\text{normalized proportion incompatible})} - 1)/24$$

Figure 9. Blood Type Rating Scale, Highlighting Blood Type Alignment



Patient Access Rating Scales

Two attributes intended to increase lung transplant access for particular groups of patients are included in the Lung CAS: prior living donor status and pediatric status.

Both attributes are binary (yes/no) and have very simple rating scales.

Prior Living Donor Rating Scale

Lung candidates are considered prior living donors if they have previously donated *any* solid organ (e.g., liver, kidney, lung lobe, etc.) in the U.S. or its territories.

Attribute Value	Rating
Yes, candidate is a prior living donor	100%
No, candidate is not a prior living donor	0%

Pediatric Age Group Rating Scale

Candidates who were less than 18 years old when added to the lung waiting list are considered to be in the pediatric age group.

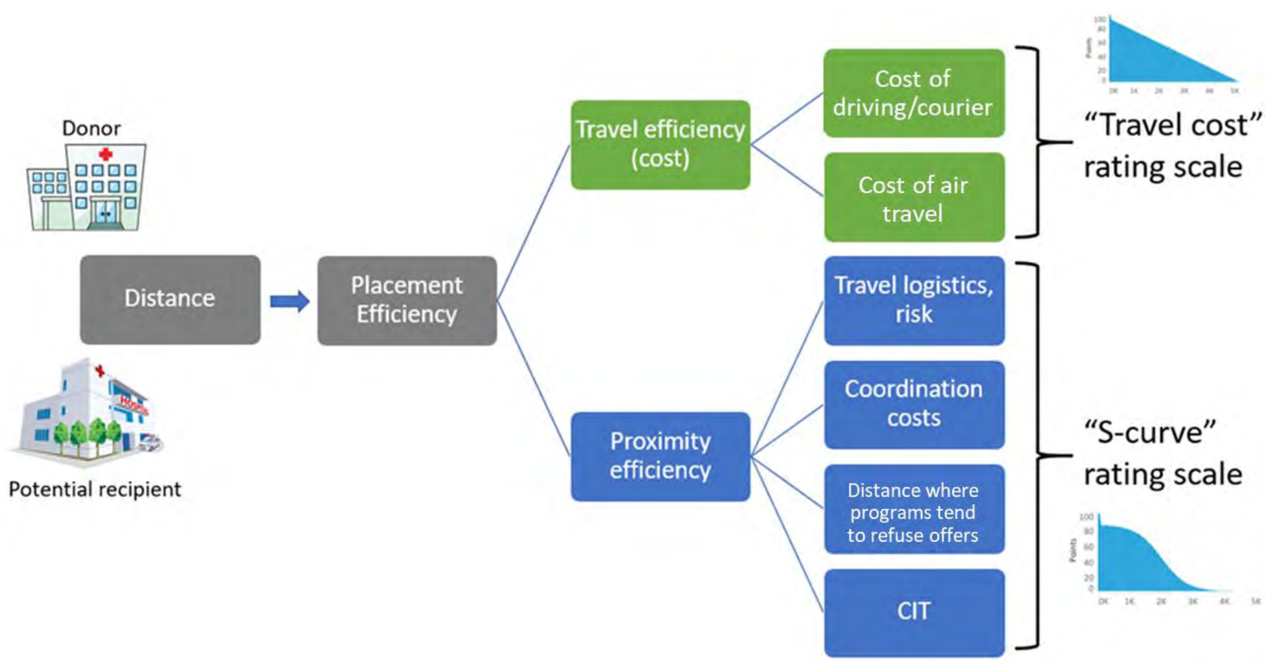
Attribute Value	Rating
Yes, candidate was under 18 at registration	100%
No, candidate was over 18 at registration	0%

Efficiency Rating Scales

The efficiency of the organ placement system is accounted for in Lung CAS by two distinct attributes, both determined by the distance between the donor hospital and a candidate's transplant hospital.

The first efficiency attribute is "travel efficiency," which accounts for the fact that transportation costs are expected to be higher, on average, for lungs transported further distances, particularly if air travel is required.

Figure 10. Costs and Inefficiencies Accounted for in the Two Efficiency Attributes

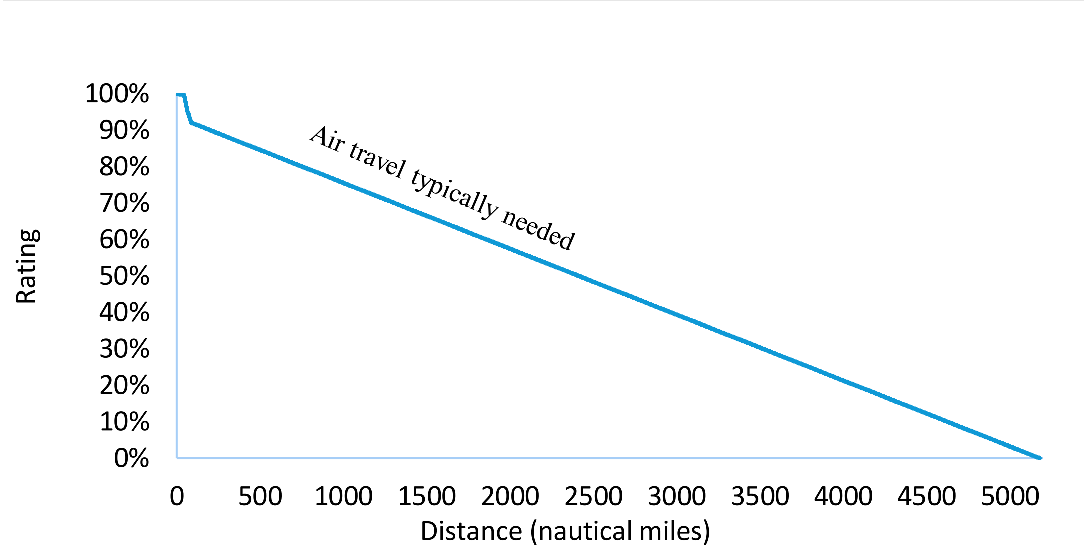


Travel Efficiency (cost) Rating Scale

The travel efficiency rating scale reflects the estimated costs of shipping organs over shorter versus longer distances between the donor and transplant hospitals. Since transportation costs are generally lower for shorter distances, the rating scale decreases as a function of distance.

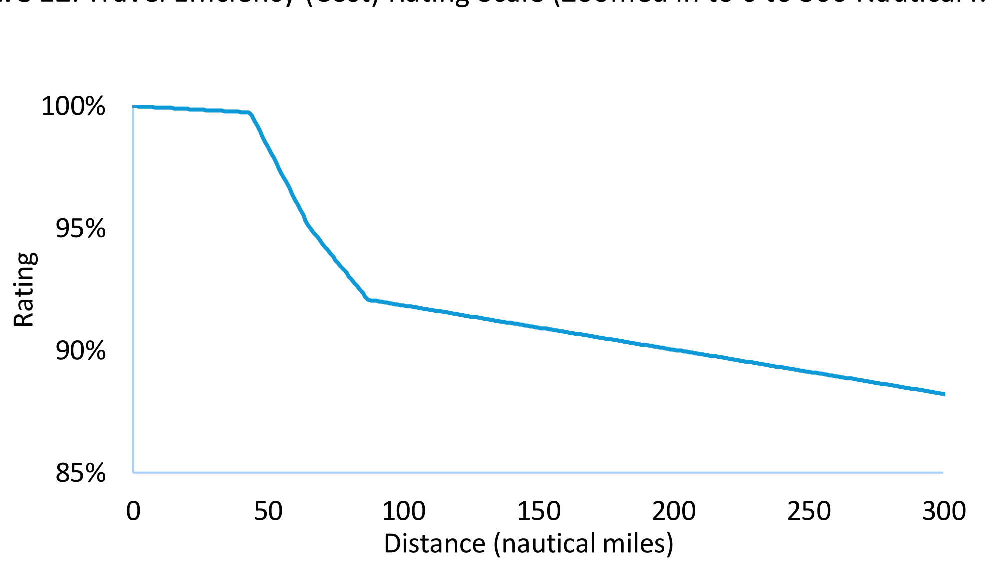
If the distance is zero, the travel efficiency rating is the highest possible value of 100%. By contrast, if the distance is 5,181 nautical miles – which is the distance between the most distant donor and transplant hospitals in the U.S. – the rating has its lowest possible value of 0%.

Figure 11. Travel Efficiency (Cost) Rating Scale



Zooming in to the first 300 nautical miles, Figure 12 shows a very shallow, decreasing slope at short distances when ground travel is expected, reflecting only slightly increased cost expected for a longer versus shorter drive. However, the rating scale declines more sharply at distances that may require air travel. Beyond a certain distance, it is estimated that lungs will nearly always be transported by air. Once traveling by air, the added cost of traveling further distances is incremental, as reflected in the relatively shallow rating scale slope.

Figure 12. Travel Efficiency (Cost) Rating Scale (Zoomed in to 0 to 300 Nautical Miles)



The travel efficiency rating scale can be expressed mathematically as follows:

Rating = (1 – [6.3*NM + 247.63 * (NM – 43.44) * I{NM > 43.44} – 104.44 * (NM – 67.17) * I{NM > 67.17} – 128.34 * (NM – 86.9) * I{NM > 86.9}] / 116989.1)

where NM = straight-line distance between donor hospital and candidate hospital in nautical miles[10]

and I () represents the indicator function that is either 1 if true or 0 if false

Proximity Efficiency Rating Scale

The proximity efficiency rating scale is intended to account for all other inefficiencies associated with transporting lungs further distances, besides actual transportation costs. For example, as shown above in Figure 10, this attribute accounts for factors such coordination costs, risk of travel to personnel and organs, as well as potentially detrimental effects of organ ischemia associated with transporting lungs distances well beyond typical practice.

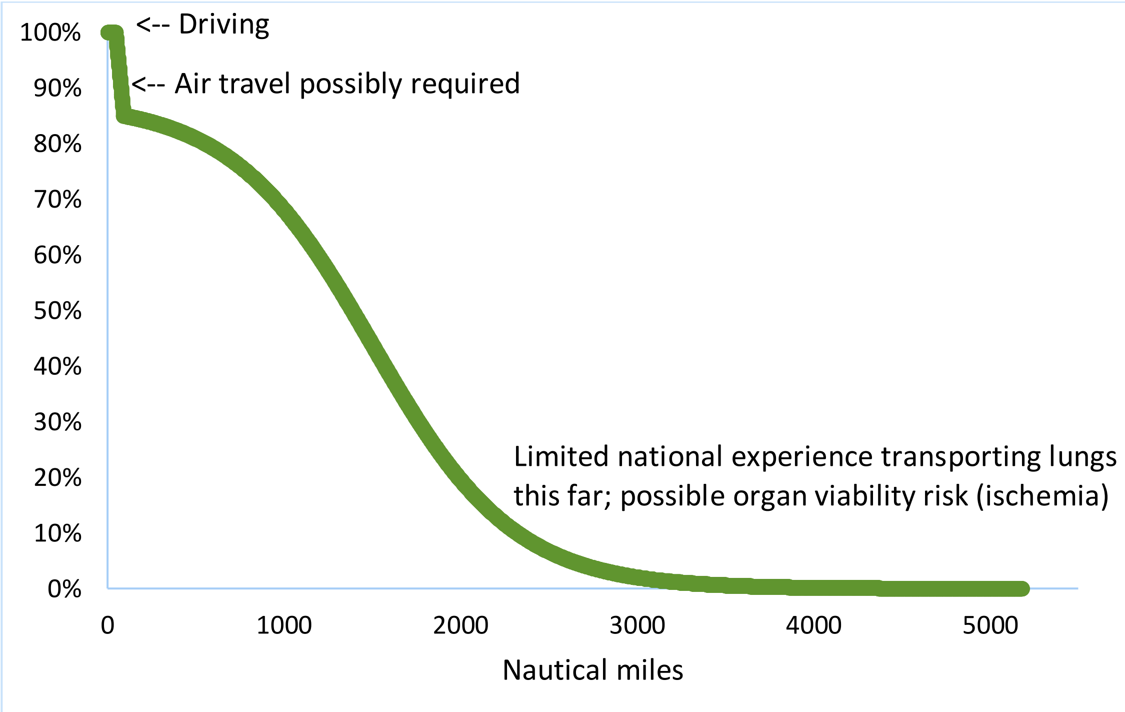
This rating scale was derived through committee deliberations, leveraging the subject matter expertise of committee members involved in the transportation of donated lungs. The proximity efficiency rating achieves its highest possible value of 100% when the donor and transplant hospitals are less than or equal to 45 nautical miles apart, reflecting no incremental inefficiencies if ground transportation is expected to be feasible.

Beyond about 90 nautical miles, lungs are expected to almost always require air travel, and the rating scale drops to 85%, reflecting inefficiencies associated with arranging and taking flights by dropping. After 90 miles, the rest of the rating scale is determined by a sigmoidal mathematical function, or "S-curve." The shallow slope at the beginning of the S-curve reflects the belief that inefficiencies are not very different among air transports of varying distances within a relatively nearby range.

However, the S-curve decreases much more rapidly as distances exceed typical practice (i.e., beyond about 1000 nautical miles), due to increased logistical complexity, potential risks to organ viability due to ischemia, and other inefficiencies. The rating scale drops to near zero after 3,000 nautical miles. However, since the lung continuous distribution policy does not include any absolute distance boundaries, a candidate <u>any distance away</u> from the donor hospital can still potentially be prioritized ahead of nearby candidates, if the candidate's Lung CAS is high based on other attributes in the score.

[10] The distance between the donor and transplant hospitals is calculated based on the latitude and longitude associated with the hospitals' physical addresses, as contained in the OPTN database, using the Haversine method. Distance in nautical miles is rounded to the nearest integer using the 'floor' function (e.g., a distance of 0.6 will be rounded to 0).

Figure 13. Proximity Efficiency ("S-Curve") Rating Scale



The proximity efficiency rating scale is expressed mathematically as follows:

Rating = I {NM≤45} + {NM ∈(45,90)} × (1−0.15/45×(NM−45)) + I{NM≥90} × 0.875/ [1+exp [0.0025×(NM−1500)]

where NM = straight-line distance between donor hospital and candidate hospital in nautical miles[9]

and I() represents the indicator function that is either 1 if true or 0 if false

Example Lung CAS Calculations

This section of the guide provides several example scenarios to illustrate how the Lung CAS is calculated using the steps outlined below.

1. Determine the candidate's attributes
2. Determine the candidate's attribute ratings for each of the nine attributes
3. Multiply each attribute rating by the associated attribute weight in Table 1
4. Add all nine products from step 3 together

Example Candidate #1

Step 1. Determine the candidate's attributes.

Attribute	Value for Candidate 1
WLAUC	247
PTAUC	1361
Priority Status	1
ABO	O
CPRA	0.530490
Height (cm), and diagnosis group	141, diagnosis group C
Age (years)	10
Prior Living Donor	False
Distance from donor hospital	40 NM

Step 2. Determine the candidate's attribute ratings for each of the nine attributes.

Attribute	Value for Candidate 1	Rating Scale	Attribute Rating
WLAUC	247	$(25^{(1-247/365)} - 1)/24$	7.63%
PTAUC	1361	1361/1826	74.53%
ABO	O	$(25^{\text{Normalized proportion incompatible}}-1)/24$	100%
CPRA	0.53049	$(100^{\text{CPRA}}-1)/99$	10.61%
Height (cm), and diagnosis group	141, diagnosis group C	$(100^{\text{Proportion height incompatible}} -1)/99$	21.06%
Pediatric	True	0/1	100%
Prior Living Donor	False	0/1	0%
Proximity Efficiency	40 NM	$I\{NM\leq45\} + I\{NM \in(45,90)\} \times (1-0.15/45 \times (NM-45)) + I\{NM\geq90\} \times 0.875/ [1 + \exp[0.0025 \times (NM-1500)]$	100%
Travel Efficiency	40 NM	(1 – [6.3*NM + 247.63 * (NM – 43.44) * I{NM > 43.44} – 104.44 * (NM – 67.17) * I{NM > 67.17} – 128.34 * (NM – 86.9) * I{NM > 86.9}] / 116989.1)	98.80%

Step 3. Multiply each attribute weight by the attribute rating.

Lung CAS = (W_{WLAUC} x R_{WLAUC} + W_{PTAUC} x R_{PTAUC} + W_{ABO} x R_{ABO} + W_{CPRA} x R_{CPRA} + W_{HGT} x R_{HGT} + W_{PED} x R_{PED} + W_{PLD} x R_{PLD} + W_{EFF} x R_{EFF} + W_{COST} x R_{COST})

25 x 7.63% + 25 x 74.53% + 5 x 100% + 5 x 10.61% + 5 x 21.06% + 20 x 100% + 5 x 0% + 5 x 100% + 5 x 98.80%

Step 4. Add all nine products from step 3 together.

=WALUC sub-score + PTAUC sub-score + ABO sub-score + CPRA sub-score + HGT sub-score + Pediatric sub-score + Prior Living Donor sub-score + Proximity Efficiency sub-score + Travel Efficiency sub-score

=1.9075 + 18.6325 + 5.0000 + 0.5305 + 1.0530 + 20.0000 + 0.0000 + 5.0000 + 4.9400

=57.0635

Example Candidate #2

Step 1. Determine the candidate's attributes.

Attribute	Value for Candidate 2
WLAUC	347 days
PTAUC	1650 days
ABO	O
CPRA	0.999999
Height (cm), diagnosis group	91, diagnosis group B
Age (years)	16
Prior Living Donor	False
Distance from donor hospital	120 NM

Step 2. Determine the candidate's attribute ratings for each of the nine attributes.

Attribute	Value for Candidate 2	Rating Scale	Attribute Rating
WLAUC	347	$(25^{(1\text{-WLAUC}/365)} – 1)/24$	0.72%
PTAUC	1650	PTAUC/1826	90.36%
ABO	O	$(25^{\text{Normalized proportion incompatible}}\text{-}1)/24$	100%
CPRA	0.999999	$(100^{\text{CPRA}}\text{-}1)/99$	100%
Height (cm), and diagnosis group	91, diagnosis group B	$(100^{\text{Proportion height incompatible}}\text{-}1)/99$	98.82%
Pediatric	True	0/1	100%
Prior Living Donor	False	0/1	0%
Proximity Efficiency	120 NM	$I\{NM≤45\} + I\{NM ∈(45,90)\} × (1−0.15/45 × (NM−45)) + I\{NM≥90\} × 0.875/ [1 + \exp[0.0025 × (NM−1500)]$	84.81%
Travel Efficiency	120 NM	(1 – [6.3*NM + 247.63 * (NM – 43.44) * I{NM > 43.44} – 104.44 * (NM – 67.17) * I{NM > 67.17} – 128.34 * (NM – 86.9) * I{NM > 86.9}] / 116989.15)	90.60%

Step 3. Multiply each attribute weight by the attribute rating.

Lung CAS = (W_{WLAUC} x R_{WLAUC} + W_{PTAUC} x R_{PTAUC} + W_{ABO} x R_{ABO} + W_{CPRA} x R_{CPRA} + W_{HGT} x R_{HGT} + W_{PED} x R_{PED} + W_{PLD} x R_{PLD} + W_{EFF} x R_{EFF} + W_{COST} x R_{COST})

Lung CAS = 25 x 0.72% + 25 x 90.36% + 5 x 100% + 5 x 100% + 5 x 98.82% + 20 x 100% + 5 x 0% + 5 x 84.81% + 5 x 90.60%

Step 4. Add all nine products from step 3 together.

=WALUC sub-score + PTAUC sub-score + ABO sub-score + CPRA sub-score + HGT sub-score + Pediatric sub-score + Prior Living Donor sub-score + Proximity Efficiency sub-score + Travel Efficiency sub-score

=0.1800 + 22.5900 + 5.0000 + 5.0000 + 4.9410 + 20.0000 + 0.0000 + 4.2405 + 4.5300

=66.4815

Example Candidate #3

Step 1. Determine the candidate's attributes.

Attribute	Value for Candidate 3
WLAUC	200 days
PTAUC	1270 days
ABO	B
CPRA	0.508875
Height (cm), diagnosis group	195, diagnosis group D
Age (years)	69
Prior Living Donor	True
Distance from donor hospital	260 NM

Step 2. Determine the candidate's attribute ratings for each of the nine attributes.

Attribute	Value for Candidate 3	Rating Scale	Attribute Rating
WLAUC	200	$(25^{(1\text{-WLAUC}/365)} - 1)/24$	13.69%
PTAUC	1270	PTAUC/1826	69.55%
ABO	B	$(25^{\text{Normalized proportion incompatible}}\text{-}1)/24$	44.764%
CPRA	0.508875	$(100^{\text{CPRA}}\text{-}1)/99$	9.51%
Height (cm), and diagnosis group	195, diagnosis group D	$(100^{\text{Proportion height incompatible}}\text{-}1)/99$	18.23%
Pediatric	False	0/1	0%
Prior Living Donor	True	0/ 1	100%
Proximity Efficiency	260 NM	I\{NM≤45\} + I\{NM ∈(45,90)\} × (1−0.15/45 × (NM−45)) + I\{NM≥90\} × 0.875/ [1 + exp[0.0025 × (NM−1500)]	83.73%
Travel Efficiency	260 NM	(1 – [6.3*NM + 247.63 * (NM – 43.44) * I{NM > 43.44} – 104.44 * (NM – 67.17) * I{NM > 67.17} – 128.34 * (NM – 86.9) * I{NM > 86.9}] / 116989.1)	88.10%

Step 3. Multiply each attribute weight by the attribute rating.

Lung CAS = (W_{WLAUC} x R_{WLAUC} + W_{PTAUC} x R_{PTAUC} + W_{ABO} x R_{ABO} + W_{CPRA} x R_{CPRA} + W_{HGT} x R_{HGT} + W_{PED} x R_{PED} + W_{PLD} x R_{PLD} + W_{EFF} x R_{EFF} + W_{COST} x R_{COST})

Lung CAS = 25 x 13.69% + 25 x 69.55% + 5 x 44.764% + 5 x 9.51% + 5 x 18.23% + 20 x 0% + 5 x 100% + 5 x 83.73% + 5 x 88.10%

Step 4. Add all nine products from step 3 together

=WALUC sub-score + PTAUC sub-score + ABO sub-score + CPRA sub-score + HGT sub-score + Pediatric sub-score + Prior Living Donor sub-score + Proximity Efficiency sub-score + Travel Efficiency sub-score

= 3.4225 + 17.3875 + 2.2382 + 0.4755 + 0.9115 + 0.0000 + 5.0000 + 4.1865 + 4.4050

=38.0267

Appendix 1. Guide to Calculating WLAUC and PTAUC

This appendix describes how to calculate the 1-year waitlist urgency score (WLAUC) and the 5-year post-transplant survival score (PTAUC).

What is WLAUC?

The WLAUC stands for the 1-year waitlist urgency score. It refers to the waiting list "area under the curve," and is derived from the area under the estimated average 1-year survival curve for each candidate. This area provides an estimate of the average number of days of survival without a transplant out of the maximum possible (365) days in a year. It does not predict the total time any patient may survive, which may be longer than one year. The WLAUC calculations used in the Lung CAS are the same as the WLAUC calculations used in the LAS calculation.

What is PTAUC?

The PTAUC refers to the post-transplant "area under the curve," and is derived from the area under the estimated average 5-year survival curve for each candidate. This area provides an estimate of the average number of days of survival with a transplant out of the maximum possible (1826) days in 5 years. It does not predict the total survival time for any patient, which may be longer than five years. The PTAUC calculations used in the Lung CAS are similar to the PTAUC calculations used in the LAS calculation, with the only difference being that the post-transplant survival component has been changed from a 1-year measure to a 5-year measure.

How is the WLAUC and PTAUC calculated?

We've computed the WLAUC and PTAUC for a hypothetical candidate to help you understand the process.

The following description of the calculation of WLAUC and PTAUC in this document assumes that all characteristics are known. With the exception of a few characteristics (e.g., age and diagnosis), the WLAUC and PTAUC can also be computed when characteristics are missing. If a characteristic is missing, such as creatinine level or BMI, a default value is used. For some characteristics the default value is a normal value for that characteristic; for other characteristics the default is the least beneficial value for that characteristic. A normal value is a value that a person healthy for the given characteristic would exhibit. The least beneficial value is the value for that characteristic that will yield the lowest WLAUC and PTAUC. In general, the least beneficial value is either the minimum or maximum possible value for the characteristic.

What is involved in the WLAUC Calculation?

Calculating the WLAUC Step by Step. A detailed explanation for each of the steps follows.

Step 1. Calculate the expected waiting list survival probability during the next year:

$$S_{WL,i}(t) = S_{WL,0}(t)e^{\beta_1 X_{1i}+\beta_2 X_{2i}+\cdots+\beta_p X_{pi}}$$

where

$S_{WL,i}(t)$ is the expected waiting list survival probability at time t for candidate i

$S_{WL,0}(t)$ is the baseline waiting list survival probability at time t i.e., the survival probability for a candidate with all characteristics at baseline values (see OPTN Policy Table 21-5: Baseline Waiting List Survival ($S_{WL}(t)$) Probability Where t=Time in Days)

$\beta_1, \beta_2, \ldots \beta_p$ are the parameter estimates from the waiting list model (see OPTN Policy Table 21-3 provides the covariates and their coefficients for the waiting list mortality calculation)

X_{ji} is the value of characteristic j for candidate i (j = 1, 2, …, p)

i = 1, 2, …, N is the candidate identifier

Computing a candidate's expected waiting list survival probability during the next year involves three calculations:

a) Sum the product of parameter estimates and characteristic values for candidate i:

$$\beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_p X_{pi}$$

Note: For β values, see OPTN Policy Table 21-3: Waiting List Survival Calculation: Covariates and their Coefficients, which provides the covariates and their coefficients for the waiting list mortality calculation.

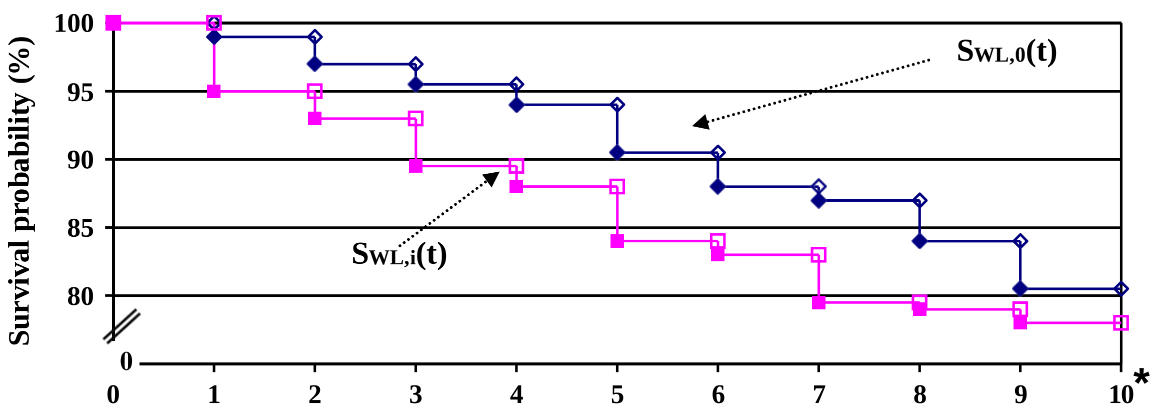
b) Exponentiate this sum: $e^{\beta_1 X_{1i}+\beta_2 X_{2i}+\cdots+\beta_p X_{pi}}$

c) Apply the exponent to the baseline survival at all time points during the next year:

$$S_{WL,0}(t)e^{\beta_1 X_{1i}+\beta_2 X_{2i}+\cdots+\beta_p X_{pi}}$$

Note: For baseline survival values, see OPTN Policy Table 21-5: Baseline Waiting List Survival ($S_{WL}(t)$) Probability Where t=Time in Days.

Step 1c adjusts the baseline survival at each time point ($S_{WL,0}(t)$) by the candidate's characteristics to yield the expected waiting list survival probability for the candidate, $S_{WL,i}(t)$. The resulting survival may be either higher or lower than the baseline survival. A hypothetical example, in which the expected survival for candidate i is lower than the baseline survival, follows:



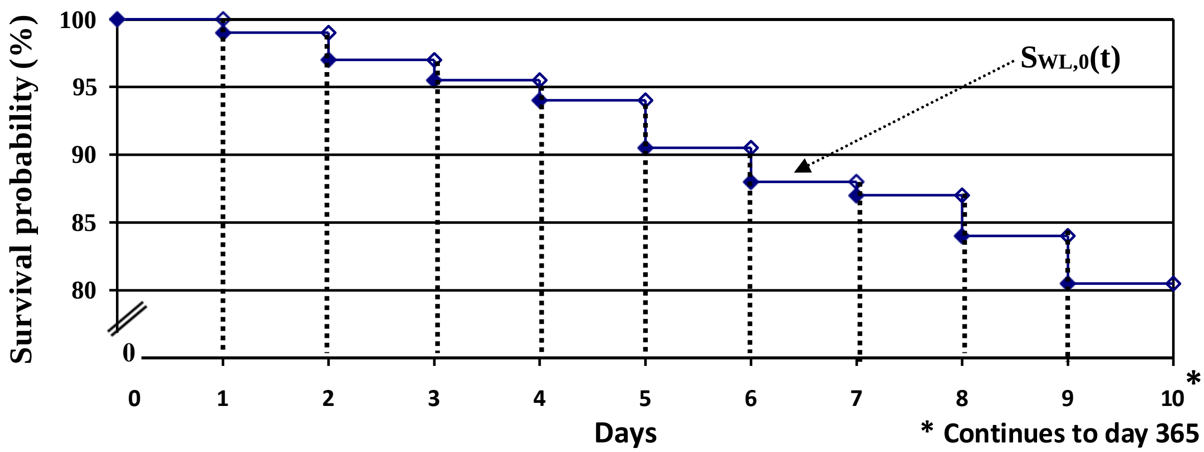
*Continues to day 365

Step 2. Calculate the *area under the waiting list survival probability curve during the next year on the waiting list:*

The area under the waiting list survival probability curve can be interpreted as the number of days a candidate with a specified set of characteristics is expected to live during the next year on the waiting list.

Since the baseline survival, $S_{WL,0}(t)$, is based on information collected on a per-day basis (e.g., patients alive or having died per day) rather than an hourly basis, the survival probability stays the same during an entire day. This results in a "curve" that is actually a large set of stair-steps. Similarly the candidate's waiting list survival curve, $S_{WL,i}(t)$, is also a stair-step function but with different heights for the steps (as shown in the previous figure).

In this example, the area under the baseline survival curve, $S_{WL,0}(t)$, can be computed as the sum of the areas of the rectangles, where the width is 1 day and the height is the survival rate on that day:



Each candidate's set of characteristics will adjust the height of each rectangle: $S_{WL,0}(t)$ is adjusted by the candidate's characteristics to $S_{WL,i}(t)$. The height of the rectangle for candidate i from 0 to 1 day is $S_{WL,i}(0)$, from 1 to 2 days the rectangle's height is $S_{WL,i}(1)$, and so on. The width of the rectangles remains the same for all candidates: 1 day.

For candidate I, the area under the waiting list survival probability curve during the next 1 year, can be written mathematically as:

$$WL_i = \sum_{K=1}^{365} Height_k * Width_k = \sum_{k=1}^{365} S_{WL,i}\,(k-1) * 1\ day$$

Theoretically WL_i can range from approximately 0 days (if the expected survival is 0 at day 1) to 365 days (if the expected survival is 100% during the entire next year on the waiting list). But these are the most extreme cases; most candidates will have a WL_i value greater than 0 but less than 365 days.

What is involved in the PTAUC Calculation?

Step 1. Calculate the expected post-transplant survival probability during the first 5 years post-transplant:

$$S_{TX,i}(t) = S_{TX,0}(t)^{e^{\alpha_1 Y_{1i} + \alpha_2 Y_{2i} + \cdots + \alpha_q Y_{qi}}}$$

where:

$S_{TX,i}(t)$ is the expected post-transplant survival probability at time t for candidate i

$S_{TX,0}(t)$ is the baseline post-transplant survival probability at time t, i.e., the survival probability for a candidate with all characteristics at the baseline value (see OPTN Policy Table 21-8: Baseline Post-Transplant Survival (S_{TX}(t)) Probability Where t=Time in Days)

$\alpha_1, \alpha_2, \ldots \alpha_q$ are the parameter estimates from the post-transplant model (see OPTN Policy Table 21-6: Post-Transplant Outcomes Calculation: Covariates and Their Coefficients)

Y_{ji} is the value of characteristic j for candidate i (j = 1, 2, …, q)

$i = 1, 2, \ldots, N$ is the candidate identifier

This is the same calculation as was performed in Step 1 of the WLAUC calculation, but now the characteristics, parameter estimates and baseline survival are for the post-transplant period rather than for the waiting period.

As with the waiting list survival probability computation, the expected post-transplant survival probability computation requires 3 separate calculations:

a) Sum the product of parameter estimates and characteristic values for candidate i: $\alpha_1 Y_{1i} + \alpha_2 Y_{2i} + \cdots + \alpha_q Y_{qi}$

   Note: For α values see OPTN Policy Table 21-6: Post-Transplant Outcomes Calculation: Covariates and Coefficients.

b) Exponentiate this sum: $\boldsymbol{e^{\alpha_1 Y_{1i} + \alpha_2 Y_{2i} + \cdots + \alpha_q Y_{qi}}}$

c) Apply the exponent to the baseline survival at all time points during the first 5 years post-transplant: $\boldsymbol{S_{TX,0}(t)^{e^{\alpha_1 Y_{1i} + \alpha_2 Y_{2i} + \cdots + \alpha_q Y_{qi}}}}$

   Note: For baseline values, see OPTN Policy Table 21-8: Baseline Post-Transplant Survival ($S_{TX}(t)$) Probability, where t=Time in Days.

Step 2. Calculate *the area under the post-transplant probability curve during the first 5 years post-transplant*:

The logic for this computation is identical to the waiting list side. It can be calculated by summing the area of rectangles with height of $S_{TX,i}(t)$ and width of 1 day.

$$PT_i = \sum_{k=1}^{1826} Height_k * Width_k = \sum_{k=1}^{1826} S_{TX,i}(k-1) * 1\ day$$

As with WL_i, the theoretical range of PT_i is 0 days to 1826 days, though most candidates will fall somewhere in between.

Example WLAUC and PTAUC Calculations

Assume that Candidate Z has the following set of characteristics:

Characteristic	Value for Candidate Z
Diagnosis	Emphysema (Group A)
Age	51 years
Height	5 ft. 8 in. (1.727 m)
Weight	165 lbs (74.84 kg)
Diabetes	Not diabetic
Functional status	No assistance needed with activities of daily living
FVC (% predicted)	50%
PA systolic pressure	40 mm Hg
PCW pressure	10 mm Hg
O_2 required at rest	2 L/min
Six-minute walk distance	800 ft
Continuous mechanical ventilation	Not on continuous mechanical ventilation
PCO_2	52 mm Hg
Increase in PCO_2 (%)	30%
Creatinine	1.0 mg/dl

BMI = weight (kg)/height (m)^2
= 74.84 kg/(1.727 m)^2
= 25.0928 kg/m^2

Calculating the WLAUC Step by Step

Step 1. Calculate the waiting list survival probability:

$$S_{WL,Z}(t) = S_{WL,0}(t)^{e^{\beta_1 X_{1z} + \beta_2 X_{2z} + \cdots + \beta_p X_{pz}}}$$

a) First, sum the product of parameter estimates and characteristic values for candidate:
$\beta_1 X_{1z} + \beta_2 X_{2z} + \cdots + \beta_p X_{pz}$

Characteristic	Value for Candidate Z (X_{pz}†)	β_p¥	$\beta_p * X_{pz}$
Age at the time of the match run (fractional calendar year)	51	0.0281444188123287* age	1.435365
Bilirubin (mg/dL)	1	0.15572123729572 *(bilirubin – 1)	0
BMI (kg/m^2)	25.0928 kg/m^2	0	0
Assisted ventilation	Not ECMO or continuous mechanical-hospitalized	0	0
Creatinine (serum) (mg/dL) with the most recent test date and time	1 mg/dL	0.0996197163645* creatinine	0.099620
Diagnosis Group	Diagnosis Group A	0	0
Functional status	No assistance needed with activities of daily living	-0.59790409246653	-0.597904
Oxygen needed to maintain adequate oxygen saturation (88% or greater) at rest (L/min) for Diagnosis Group A	2 L/min	0.08232292818591*O_2	0.164646
PCO_2 (mm Hg): current (PCO_2 is at least 40 mm Hg)	52	0.12639905519026*PCO_2/10	0.657275
PCO_2 threshold change: (Increase in PCO2 of 15% or greater within a 6-month period)	30%	0.15556911866376	0.155570
Pulmonary artery (PA) systolic pressure (mm Hg) at rest, prior to any exercise	Diagnosis Group A and the PA systolic pressure is 40 mm Hg or less	0	0
Six-minute walk distance (feet) Obtained while the candidate is receiving supplemental oxygen required to maintain an oxygen saturation of 88% or greater at rest	800 ft	-0.09937981549564*Six-minute-walk distance/100	-0.795039
Total	$\beta_1 X_{1z} + \beta_2 X_{2z} + \cdots + \beta_p X_{pz} = 1.119533$		

Note: If the characteristic is dichotomous (e.g., Yes/No) and the candidate does not have the characteristic, the value of X is 0. If the candidate does have the characteristic X = 1.

¥ For β values see OPTN Policy Table 21-3: Waiting List Survival Calculation: Covariates and their Coefficients

b) Exponentiate this sum: $e^{\beta_1 X_{1i}+\beta_2 X_{2i}+\cdots+\beta_p X_{pi}} = e^{1.119533} = 3.063423$

c) Apply the exponent to the baseline survival at all time points during the next year.

Time (days) = t	Baseline waiting list survival = $S_{WL,O}(t)$*	$S_{WL,z}(t) = S_{WL,O}(t)^{3.082901}$
0	1	1
1	0.999998	0.999992
2	0.999983	0.999947
3	0.999956	0.999866
4	0.999928	0.999778
5	0.999902	0.999699
6	0.999878	0.999626
7	0.999856	0.999559
8	0.999814	0.999431
9	0.999786	0.999346
10	0.999770	0.999295
…	…	….
364	0.994390	0.982912
$\sum S_{WL}$ = WL	363.927888	361.728157

*Baseline waiting list survival excerpted from OPTN Policy Table 21-5: Baseline Waiting List Survival ($S_{WL}(t)$) Probability Where t=Time in Days

Step 2. Calculate the waitlist urgency measure:

$$WL_Z = \sum_{k=1}^{365} S_{WL,Z}(k-1) * 1\ day = 361.72\ days$$

Calculating the PTUAC Step by Step

Step 1. Calculate the post-transplant survival probability during the first 5 years post-transplant:

$$S_{TX,z}(t) = S_{TX,0}(t)^{e^{\alpha_1 Y_{1z}+\alpha_2 Y_{2z}+\cdots+\alpha_q Y_{qz}}}$$

a) First, sum the product of parameter estimates and characteristic values for candidate:

$$\alpha_1 Y_{1z} + \alpha_2 Y_{2z} + \cdots + \alpha_q Y_{qz}$$

Characteristic (Y)		Value for Candidate Z (Yqz†)	α q[¥]	α q*Yqz
Age at the time of the match run (fractional calendar year)	Age is at least 50 and less than 60	51	0.0167463361760962 x (age - 50) + 0.02590812	0.042654456
Creatinine (serum) (mg/dL) with the most recent test date and time	Creatinine is at least 0.8 and less than 1.4 and candidate is at least 18 years old	1.0 mg/dl	0.6844301806854400 x (creatinine - 0.8) + 0.24129311	0.378179146
Cardiac index (L/min/m^2) at rest, prior to any exercise	Less than 2 L/min/m^2	1 L/min/m^2	-0.4837491139906200 x (2 – cardiac index) + 0.04030226	-0.443446854
Assisted ventilation		Not ECMO or continuous mechanical-hospitalized	0	0
Diagnosis Group		A	-0.098901796	-0.098901796
Functional Status		Requires no assistance to perform activities of daily living	-0.005304128	-0.005304128
Six-minute-walk distance (feet) obtained while candidate is receiving supplemental oxygen required to maintain an oxygen saturation of 88% or greater at rest. Increase in supplemental oxygen.	At least 800 feet and less than 1,200 feet	800 ft	-0.0001950464256370 x (Six-minute-walk distance - 800) - 0.00297703	-0.00297703
Total	$\alpha_1 X_{1z} + \alpha_2 X_{2z} + \cdots + \alpha_p X_{pz} = -0.129796206$			

†Note: If the characteristic is dichotomous (e.g., Yes/No) and the candidate does not have the characteristic, the value of Y is 0. If the candidate does have the characteristic Y = 1.
¥For α values see OPTN Policy Table 21-6: Post-Transplant Outcomes Calculation: Covariates and Their Coefficients

b) Exponentiate the sum: $e^{\alpha_1 Y_{1i}+\alpha_2 Y_{2i}+\cdots+\alpha_q Y_{qi}} = e^{-0.129796206} = 0.8782744$

c) Compute the post-transplant survival probabilities at each time point for Candidate Z.

Time (days) = t	Baseline post-transplant survival = $S_{TX,O}(t)$*	$S_{TX,Z}(t) = S_{TX,O}(t)^{0.8782744}$
0	1	1
1	0.999154	0.999257
2	0.998058	0.998294
3	0.997111	0.997462
4	0.996312	0.996760
5	0.995562	0.996102
6	0.995162	0.995750
7	0.994562	0.995222
8	0.994011	0.994738
9	0.99336	0.994166
10	0.992859	0.993726
…	…	…
1826	0.756169	0.782337
$\sum S_{TX}$ = PT	1580.839	1608.437221

*Baseline post-transplant survival excerpted from OPTN Policy Table 21-8: Baseline Post-Transplant Survival ($S_{TX}(t)$) Probability Where t=Time in Days

Step 2. Calculate the post-transplant survival measure:

$PT_i = \sum_{k=1}^{1826} S_{TX,i}(k-1) * 1\ day = 1608.43$ days