

1 *Original Article (Clinical Original)*

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3 **Impact of chronic lung allograft dysfunction, especially restrictive allograft**
4 **syndrome, on the survival after living-donor lobar lung transplantation compared**
5 **with cadaveric lung transplantation in adults: A single-center experience**

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18

1 **Abstract**

2 **Purpose:** The differences in chronic lung allograft dysfunction (CLAD) between living-
3 donor lobar lung transplantation (LDLLT) and cadaveric lung transplantation (CLT) remain
4 unclear. We conducted this study to compare the impact of CLAD on the outcomes after
5 LDLLT vs. CLT.

6 **Methods:** We conducted a retrospective review of the data of 97 recipients of bilateral
7 lung transplantation, including 51 recipients of LDLLT and 46 recipients of CLT.

8 **Results:** The CLAD-free survival and overall survival after LDLLT were similar to those
9 after CLT. CLAD and restrictive allograft syndrome (RAS), but not bronchiolitis obliterans
10 syndrome (BOS), developed significantly later after LDLLT than after CLT ($p = 0.015$ and
11 $p = 0.035$). Consequently, patients with CLAD and RAS, but not those with BOS, after
12 LDLLT had a significantly better overall survival than those after CLT ($p = 0.037$ and $p =$
13 0.0006). Furthermore, after the diagnosis of CLAD, the survival of patients with RAS after
14 LDLLT tended to be better than that after CLT ($p = 0.083$).

15 **Conclusion:** CLAD, especially RAS, appears to develop later after LDLLT than after CLT
16 and seems to have a lower impact on the overall survival after LDLLT than that after CLT.

17

18 **Keywords:** lung transplantation; chronic lung allograft dysfunction; bronchiolitis
19 obliterans syndrome; restrictive allograft syndrome; living-donor; rejection

1 **Introduction**

2 Living-donor lobar lung transplantation (LDLLT) has become an established treatment for
3 end-stage lung diseases [1-3] and has been shown to result in a similar survival to
4 cadaveric lung transplantation (CLT) [3]. Similar to the case after CLT, chronic lung
5 allograft dysfunction (CLAD) is a major obstacle hampering the long-term survival after
6 LDLLT [2, 3].

7 In bilateral LDLLT, because the right and left lower lobes of the lungs from two
8 different donors are implanted in the recipient in place of the entire lungs, the different
9 immunological features between the two donor lungs may affect the characteristics of
10 CLAD after LDLLT. Indeed, CLAD has been shown to develop predominantly on one side
11 after bilateral LDLLT [4]. Furthermore, morphologically, size mismatch between the chest
12 cavity of the recipient and the donor lobar lungs might also affect the development of
13 CLAD after LDLLT [5]. It was shown more than a decade ago that the rate of freedom
14 from bronchiolitis obliterans syndrome (BOS) did not differ markedly between LDLLT and
15 CLT [6]; however, since the introduction of the concept of restrictive allograft syndrome
16 (RAS) [7], little information has been obtained regarding the differences in the phenotypes
17 of CLAD between LDLLT and CLT, especially in relation to the long-term outcomes of
18 CLAD.

19 In the present study, we compared the impact of CLAD on the long-term outcomes
20 after bilateral LDLLT vs. bilateral CLT.

21

22 **Methods**

23 *Patients*

1 This study was a retrospective review of patients who underwent bilateral lung
2 transplantation (LT) for end-stage lung disease at Okayama University Hospital between
3 October 1998 and August 2016. Patients undergoing lung retransplantation and patients
4 <18 years of age were excluded from this study in order to eliminate the effect of the initial
5 LT and the effect of physical growth on the lung function in pediatric patients. A total of 97
6 adult patients who underwent bilateral LT, including 51 recipients of bilateral LDLLT and
7 46 recipients of bilateral CLT, were included in this study. One patient underwent bilateral
8 LDLLT sparing the native right upper lobe. We assessed the preoperative and operative
9 patient characteristics and the postoperative outcomes. The lung allocation score (LAS)
10 of each patient was retrospectively calculated using the LAS calculator published on the
11 OPTN website ([https://optn.transplant.hrsa.gov/resources/allocation-calculators/las-](https://optn.transplant.hrsa.gov/resources/allocation-calculators/las-calculator/)
12 [calculator/](https://optn.transplant.hrsa.gov/resources/allocation-calculators/las-calculator/)) in November 2015 in order to establish the recipients' preoperative disease
13 severity. The CLAD-free survival was defined as the interval from LT to the onset of CLAD,
14 and the data were censored on the date of death. The overall survival was defined as the
15 interval from LT to the date of death.

16 The study protocol (No. 1803-008) was approved by the institutional review board
17 of Okayama University Hospital.

18

19 *Donor and recipient selection and the transplantation procedures*

20 Patients requiring CLT are registered with the Japan Organ Transplantation Network. The
21 allocation of organs from brain-dead donors is still based mainly on the waiting time, and
22 the LAS system has not yet been adopted in Japan. LDLLT is considered for critically ill
23 patients who cannot afford to wait for CLT. Patients hoping for LDLLT must meet all if the

1 criteria for CLT. Only blood relatives within the third degree or a spouse are accepted as
2 living donors at our institution. The size-matching protocol and transplant procedures
3 have been described in a previous report [8]. The graft ischemic time was defined as the
4 ischemic time to the second transplanted lung.

5

6 *Postoperative care*

7 The postoperative management of the recipients, including the immunosuppressive
8 therapy and prescribed prophylactic therapies against fungal and viral infections, has
9 been described elsewhere [9, 10]. The patients were assigned PGD grades according to
10 the definition of primary graft dysfunction proposed by the International Society for Heart
11 and Lung Transplantation (ISHLT) [11]. LT recipients received triple immunosuppressive
12 therapy consisting of tacrolimus or cyclosporine, mycophenolate mofetil or azathioprine,
13 and a corticosteroid. The calcineurin inhibitor was initially given by the enteric route via a
14 nasogastric tube during the first period between 1998 and 2010 and by intravenous
15 administration during the second period between 2011 and 2017, followed by oral
16 administration [10]. Acute rejection episodes were treated by bolus intravenous
17 corticosteroid therapy on three consecutive days. Pulmonary function testing, including
18 measurement of the forced expiratory volume in 1 second (FEV1) to diagnose BOS
19 (obstructive CLAD) [12] and that of the total lung capacity (TLC) to diagnose RAS
20 (restrictive CLAD) [7], was performed at 3, 6, and 12 months and once every year
21 thereafter following LT. According to the classification system proposed by the ISHLT [12],
22 the baseline FEV1 value was calculated as the average of the two best FEV1 values
23 obtained at least three weeks apart, and the baseline values of other parameters of

1 pulmonary function test were taken as the average of the parameters measured at the
2 time of the best FEV1 measurements. CLAD was defined as an irreversible decline in
3 FEV1 to <80% of the baseline [12]. RAS was defined as CLAD with an irreversible decline
4 in TLC to <90% of the baseline [7]. BOS was defined as CLAD without restrictive changes
5 of RAS [7]. For a definitive diagnosis of CLAD, blood examinations, chest X-ray, computed
6 tomography of the chest, inspiratory and expiratory computed tomography volumetry,
7 ventilation-perfusion scanning, and electrocardiography were also performed at the same
8 time as the pulmonary function testing. Among these, computed tomography of the chest,
9 inspiratory and expiratory computed tomography volumetry, and ventilation-perfusion
10 scanning were mainly used to exclude other potential causes of a reduced lung function
11 [4, 7, 12, 13]. The six-minute walk test and echocardiography were performed at the same
12 time during the first five years after LT.

13

14 *Statistical analyses*

15 All statistical analyses were performed using the GraphPad Prism 7.03 software program
16 (San Diego, CA, USA). Normally distributed continuous data were expressed as the
17 means \pm standard deviations. The bivariate comparison of continuous variables was
18 performed by Student's *t*-test. Associations between categorical variables were examined
19 by Fisher's exact test. The postoperative survival rates were analyzed by the Kaplan–
20 Meier method, and the log rank test was used to compare the differences between the
21 groups. Differences were considered significant at $p < 0.05$. The results as of October 31,
22 2017, were analyzed.

23

1 **Results**

2 *Patient characteristics*

3 Table 1 summarizes the patients' characteristics. The proportion of female patients was
4 significantly higher in the LDLLT group than in the CLT group ($p = 0.0007$). The LAS of
5 the LDLLT group was significantly higher than that of the CLT group ($p < 0.0001$). In regard
6 to the donor variables, the donor age was significantly lower in the LDLLT group than in
7 the CLT group ($p < 0.0001$). While the total number of HLA-A, HLA-B, and HLA-DR
8 mismatches with the bilateral donors in the LDLLT group was significantly higher than that
9 in the CLT group ($p < 0.0001$), those of the right lung lobe donor or left lung lobe donor
10 alone in the LDLLT group were significantly lower than in the CLT group ($p < 0.0001$). The
11 total ischemic time in the LDLLT group was significantly shorter than that in the CLT group
12 ($p < 0.0001$). Furthermore, the highest grade of PGD until 72 h after the LT in the LDLLT
13 group was significantly lower than that in the CLT group ($p < 0.0001$).

14

15 *Outcomes of CLAD*

16 The CLAD-free survival after LDLLT was similar to that after CLT ($p = 0.57$) (Fig. 1), as
17 were the BOS- and RAS-free survival. In the LDLLT group, CLAD developed
18 predominantly in the lung of one side at disease onset in 19 of 22 patients, including 10
19 patients with BOS and 9 patients with RAS. The time of onset of CLAD in the LDLLT group
20 was significantly later than that in the CLT group ($p = 0.015$) (Fig. 2a). With regard to the
21 CLAD phenotypes, while the time of the onset of BOS was similar between the two groups,
22 the onset of RAS in the LDLLT group occurred significantly later than that in the CLT group
23 ($p = 0.035$) (Fig. 2b, c). One patient in the LDLLT group, who first developed the BOS

1 phenotype and thereafter the RAS phenotype, was treated for BOS according to the
2 CLAD onset type. There was no significant difference in the overall survival after LT
3 between the 2 groups ($p = 0.11$) (Fig. 3). However, patients who developed CLAD after
4 LDLLT showed a significantly better overall survival than those who developed CLAD
5 after CLT ($p = 0.037$) (Fig. 4a). Furthermore, while the overall survival of patients who
6 developed BOS after LT was similar between the two groups, patients who developed
7 RAS after LDLLT showed a significantly better overall survival than those who developed
8 RAS after CLT ($p = 0.0006$) (Fig. 4b, c). There were no significant differences in the
9 survival after the diagnosis of CLAD between the two LT groups; however, the survival of
10 patients who developed RAS after LDLLT tended to be better than that of patients who
11 developed RAS after CLT ($p = 0.083$) (Fig. 5a, b, c).

12

13 **Discussion**

14 Although the donor characteristics and the recipient characteristics were different
15 between LDLLT and CLT, the CLAD-free survival and overall survival after bilateral LT
16 were similar between the recipients of LDLLT and CLT. However, CLAD, especially RAS,
17 but not BOS, after LDLLT, developed at a later time than that after CLT. Owing to the later
18 development of CLAD or RAS after LDLLT, the recipients with CLAD or RAS after LDLLT
19 showed a favorable overall survival compared to the recipients who developed CLAD or
20 RAS after CLT. Furthermore, following the diagnosis of CLAD, the survival of patients who
21 developed RAS after LDLLT tended to be better than that of patients who developed RAS
22 after CLT. Our results suggest that CLAD after LDLLT may have a similar incidence but
23 develop at a later time compared with CLAD occurring after CLT; in addition, CLAD

1 developing after LDLLT has a lower impact on the overall survival than that developing
2 after CLT.

3 The differences in the characteristics of the donors and recipients reflected the
4 differences in the procedures between LDLLT and CLT. First, LDLLT is usually performed
5 in small adult females or pediatric patients; thus, the proportion of female recipients in the
6 LDLLT group was significantly higher than that in the CLT group. The survival of adult
7 primary LT recipients has been reported to be significantly better among females than
8 among males [14]; however, the overall survival did not differ markedly between the two
9 groups. In addition, to eliminate the influence of the effect of physical growth on the lung
10 function in pediatric patients, pediatric patients were excluded from this study. Second,
11 the preoperative severity of the disease, which was reflected by the LAS, was significantly
12 greater in the LDLLT recipients than in the CLT recipients, because LDLLT is the main
13 option for urgent LT in Japan due to the severe shortage of donor organs. As LT has been
14 shown to provide a survival benefit even for high-LAS patients if lungs are transplanted
15 from a low-risk donor [15], the overall survival after LDLLT was comparable to that after
16 CLT. Third, the mean age of the healthy living donors for LDLLT was significantly lower
17 than that of the deceased donors for CLT, and the quality of the donor lungs, as
18 represented by the lung donor score, was significantly better in the LDLLT group than in
19 the CLT group. Consequently, despite the smaller size of the pulmonary vascular bed in
20 the lobar grafts, ideal grafts were implanted with a shorter ischemic time in LDLLT, which
21 resulted in less severe PGD after LDLLT than after CLT. Because the severity of PGD has
22 been shown to be associated with the risk of CLAD [16], the less severe PGD after LDLLT
23 than after CLT may have contributed to the delayed development of CLAD after LDLLT

1 observed in this study.

2 Although LDLLT provided a similar CLAD-free survival to CLT in this study, CLAD,
3 especially RAS, developed significantly later after LDLLT than after CLT. The delayed
4 development of RAS after LDLLT may be attributed to the morphological characteristics
5 in LDLLT. After LDLLT, small lobar grafts gradually expand to fit the recipient's chest cavity
6 due to the size mismatch, leading to gradual improvement of the pulmonary function
7 parameters, especially the forced vital capacity, during the first two years after LDLLT [17].
8 This expansion of the lobar lungs during the first two years after LDLLT may contribute to
9 the delayed development of RAS after LDLLT. Furthermore, CLAD developed
10 predominantly unilaterally at the disease onset after bilateral LDLLT in this study,
11 consistent with a previously report [4]. Because LDLLT involves 2 different donors for
12 each recipient and the total number of HLA mismatches can be up to 12, the total number
13 of HLA mismatches with the bilateral donors of the LDLLT group was significantly higher
14 than with the donors of the CLT group; however, the total number of HLA mismatches with
15 the unilateral donors alone of the LDLLT group was significantly lower than that with the
16 donors of the CLT group. We therefore speculated that immunological similarity between
17 the donor lungs from blood relatives and the recipients in LDLLT might contribute to the
18 delayed development of CLAD after LDLLT [18].

19 The development of CLAD unilaterally after LDLLT appeared not to be related to
20 the delayed development of CLAD after LDLLT in this study. Because CLAD developed
21 unilaterally after bilateral LDLLT, the unaffected contralateral lung might mask the decline
22 in the pulmonary function and delay the diagnosis of CLAD after LDLLT [4]. However,
23 consistent with the results of a previous report [4], the decline in the pulmonary function

1 occurred at the same time as the diagnosis of CLAD by ventilation scintigraphy, which
2 has been shown to be more useful for the early detection of CLAD after LT than computed
3 tomography [19].

4 Regarding the survival after LT, the delayed development of CLAD and RAS, but
5 not BOS, contributed to the better overall survival in the patients who developed CLAD
6 after LDLLT than in those who developed CLAD after CLT. In CLT, oversized allografts
7 have been shown to be associated with a less frequent occurrence of BOS [5] and an
8 increased survival after LT [20]. However, in LDLLT, undersized donor grafts have been
9 shown to expand more after LDLLT than oversized donor grafts [21]. Because smaller
10 grafts were implanted in LDLLT than in CLT, as shown by the size matching in this study,
11 such mismatch might affect the outcomes after LDLLT, similar to those after CLT. Further
12 examinations will be required to investigate the association between size matching and
13 CLAD or the survival after LDLLT. However, once the recipients were diagnosed with
14 CLAD, the impact of CLAD developing after LDLLT on the survival after the disease onset
15 did not markedly differ from that of CLAD developing after CLT. Thus, lung transplant
16 physicians should be aware of the characteristics associated with the delayed
17 development of CLAD after LDLLT for appropriate long-term management, such as drug
18 dose reduction and withdrawal in maintenance immunosuppression, except for recipients
19 of LDLLT from the same donor as that for the hematopoietic stem cell transplantation.

20 Our study had several limitations. First, this was a retrospective observational study
21 conducted at a single transplant center. Second, although the follow-up period was more
22 than one year in all patients in this study, this period was still intermediate in some cases,
23 and longer follow-up periods will be required for further validation of the prognostic impact

1 of CLAD. Third, the follow-up period was significantly different between the two groups,
2 and CLAD after CLT was shown to develop later in the long-term follow-up than that after
3 LDLLT. Finally, the number of LT recipients was small, because in addition to the exclusion
4 of pediatric patients, patients who underwent single LT were also excluded from this study
5 in order to eliminate the effect of the native contralateral lungs on the lung function.
6 However, considering that LDLLT is currently performed exclusively in Japan, our study
7 provides pertinent information about the differences in the prognostic impact of CLAD
8 developing after LDLLT versus that developing after CLT.

9 In conclusion, the CLAD-free survival after LDLLT was similar to that after CLT,
10 similar to findings for the overall survival after LT. However, CLAD, especially RAS,
11 developed at a later time after LDLLT than after CLT, leading to a better overall survival
12 of patients with CLAD and RAS in the LDLLT group than in the CLT group.

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14 **Compliance with ethical standards**

15 **Conflict of interest:** Seiichiro Sugimoto and his co-authors have no conflicts of interest.

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1 **Figure legends**

2 **Fig. 1.** The CLAD-free survival after living-donor lobar lung transplantation (LDLLT) and
3 cadaveric lung transplantation (CLT). The CLAD-free survival rates were similar between
4 the recipients of LDLLT and those of CLT (5-year CLAD-free survival rate, 74.5% vs.
5 65.7%; 10-year CLAD-free survival rate, 59.6% vs. 65.7%) ($p = 0.79$).

6
7 **Fig. 2.** The interval from lung transplantation to the diagnosis of chronic lung allograft
8 dysfunction (CLAD) after living-donor lobar lung transplantation (LDLLT) and cadaveric
9 lung transplantation (CLT). (a) The CLAD onset occurred significantly later in the LDLLT
10 group than in the CLT group (1807 ± 1402 vs. 689 ± 584 days, $p = 0.015$). (b) The timing
11 of the onset of bronchiolitis obliterans syndrome (BOS) did not differ markedly between
12 the two groups (1360 ± 1319 vs. 595 ± 643 days, $p = 0.19$). (c) The timing of the onset of
13 RAS in the LDLLT group was significantly later than in the CLT group (2343 ± 1307 vs.
14 820 ± 460 days, $p = 0.035$).

15
16 **Fig. 3.** The overall survival after living-donor lobar lung transplantation (LDLLT) and
17 cadaveric lung transplantation (CLT). There was no significant difference in the overall
18 survival rates between recipients of LDLLT and those of CLT (5-year survival rate, 82.0%
19 vs. 69.6%; 10-year survival rate, 72.7% vs. 55.7%) ($p = 0.10$).

20
21 **Fig. 4.** The overall survival of patients with chronic lung allograft dysfunction (CLAD) after
22 living-donor lobar lung transplantation (LDLLT) and cadaveric lung transplantation (CLT).
23 (a) The overall survival rates of the patients developing CLAD after LDLLT were

1 significantly better than those of the patients developing CLAD after CLT (5-year survival
2 rate, 72.4% vs. 50.0%) ($p = 0.037$). (b) The survival of the patients who developed BOS
3 after LT was similar between the 2 groups ($p = 0.90$). (c) Patients developing RAS after
4 LDLLT had a significantly better survival than those who developed RAS after CLT ($p =$
5 0.0006).

6

7 **Fig. 5.** The survival after the diagnosis of chronic lung allograft dysfunction (CLAD) after
8 living-donor lobar lung transplantation (LDLLT) and cadaveric lung transplantation (CLT).
9 There was no significant difference in the survival after disease onset among patients
10 who developed CLAD ($p = 0.57$) (a), BOS ($p = 0.49$) (b), and RAS (c) ($p = 0.083$).

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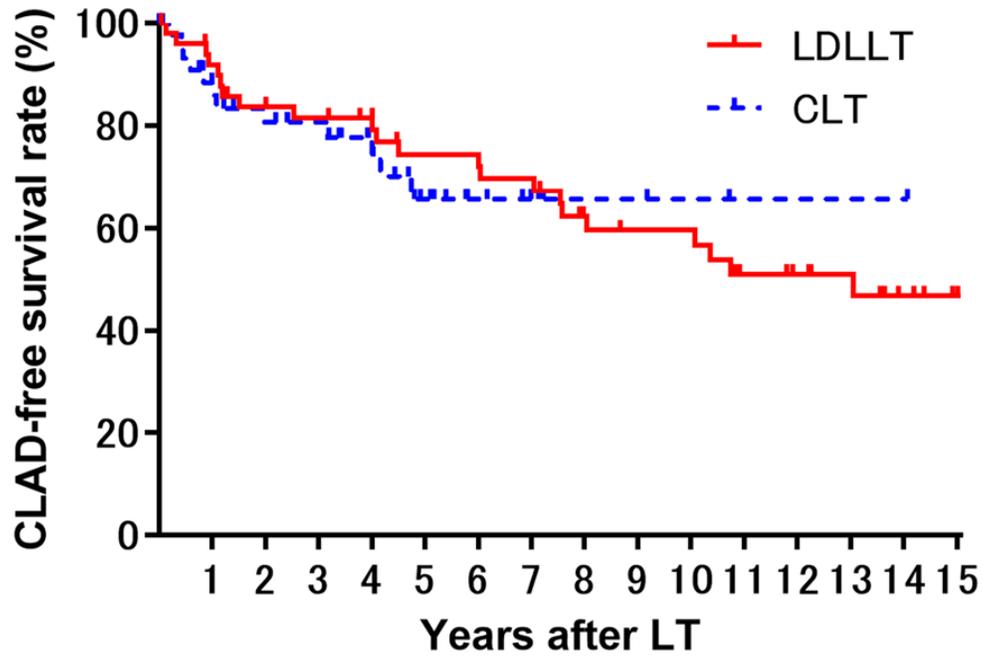
Table 1. Patient characteristics

Variables	Bilateral living-donor lobar lung transplantation	Bilateral cadaveric lung transplantation	P-value
Number of patients	51	46	
Age, years	37.5 ± 11.6	37.6 ± 12.9	0.98
Gender, female	44 (86.3%)	25 (54.3%)	0.0007
Diagnoses			
Interstitial lung disease	21 (41.2%)	11 (23.9%)	0.086
Pulmonary hypertension	11 (21.6%)	13 (28.3%)	0.49
Pulmonary GVHD	7 (13.7%)	5 (10.9%)	0.76
Lymphangioleiomyomatosis	4 (7.8%)	5 (10.9%)	0.73
Bronchiectasis	3 (5.9%)	7 (15.2%)	0.18
Other diseases	5 (9.8%)	5 (10.9%)	> 0.99
Preoperative steroid use	24 (47.1%)	18 (39.1%)	0.54
Body mass index	17.9 ± 4.0	19.5 ± 4.7	0.071
Lung allocation score	50.6 ± 15.2	39.0 ± 6.5	< 0.0001
Donor variables			
Donor age	38.5 ± 11.5	47.8 ± 12.7	< 0.0001
Donor gender, female	48 (47.1%)	19 (41.3%)	0.59
CMV mismatch (recipient negative/donor positive)	4 (7.8%)	6 (0.13%)	0.51
FVC-based size matching (%)	63.0 ± 12.1	99.5 ± 16.0	< 0.0001
Total number of HLA-A, HLA-B and HLA-DR mismatches			
Bilateral donors	6.4 ± 2.1	4.8 ± 0.8	< 0.0001
Right lung donor	3.3 ± 1.4	4.8 ± 0.8	< 0.0001
Left lung donor	3.1 ± 1.3	4.8 ± 0.8	< 0.0001
Total ischemic time (min)	163.2 ± 35.4	549.9 ± 112.7	< 0.0001
Cardiopulmonary bypass use	51 (100.0%)	45 (97.8%)	0.47
Postoperative ECMO	3 (5.9%)	6 (13.0%)	0.30
Primary graft dysfunction grade	0.9 ± 1.0	1.9 ± 1.2	< 0.0001
Acute rejection, number			
First period	1.5 ± 1.1	1.0 ± 1.1	0.21
Second period	0.3 ± 0.7	0.2 ± 0.5	0.53
30-day mortality	1 (2.0%)	2 (4.4%)	0.60
Postoperative GERD	2 (3.9%)	0	0.50
CLAD	22 (43.1%)	12 (26.1%)	0.09
BOS	12 (23.5%)	7 (15.2%)	0.44
RAS	10 (19.6%)	5 (10.9%)	0.27
Time since transplant to follow-up (days)	3514 ± 1984	1601 ± 1057	< 0.0001

BOS, bronchiolitis obliterans syndrome; CLAD, chronic lung allograft dysfunction; ECMO, extracorporeal membrane oxygenation; FVC, forced vital capacity; GERD, gastroesophageal reflux disease; GVHD, graft-versus-host disease; HLA, human leucocyte antigen; PGD, primary graft dysfunction; RAS, restrictive allograft syndrome

1

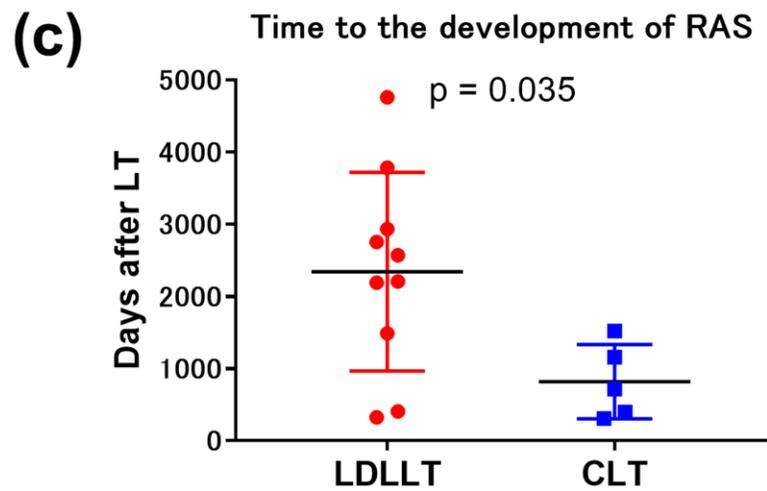
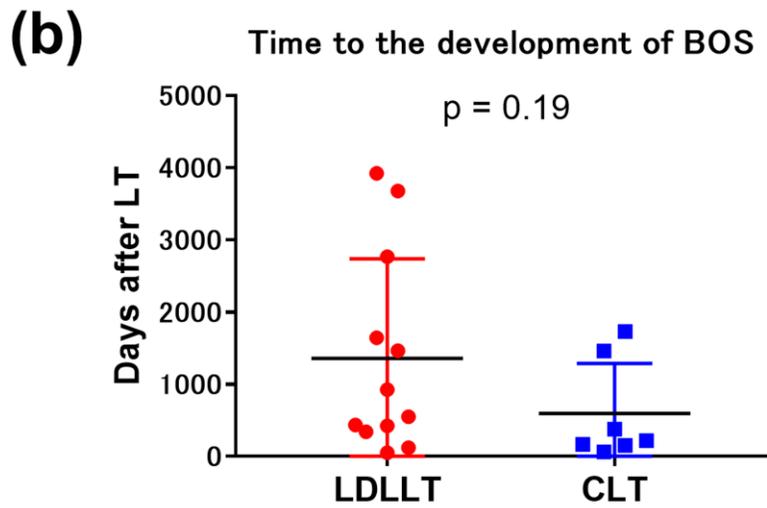
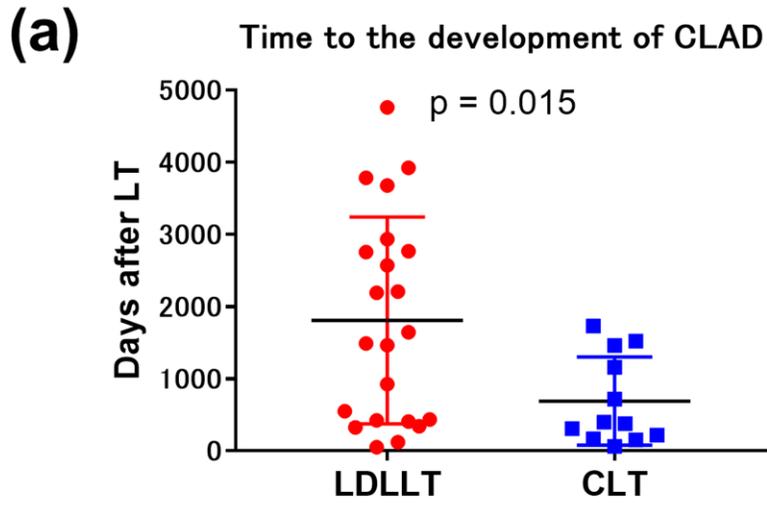
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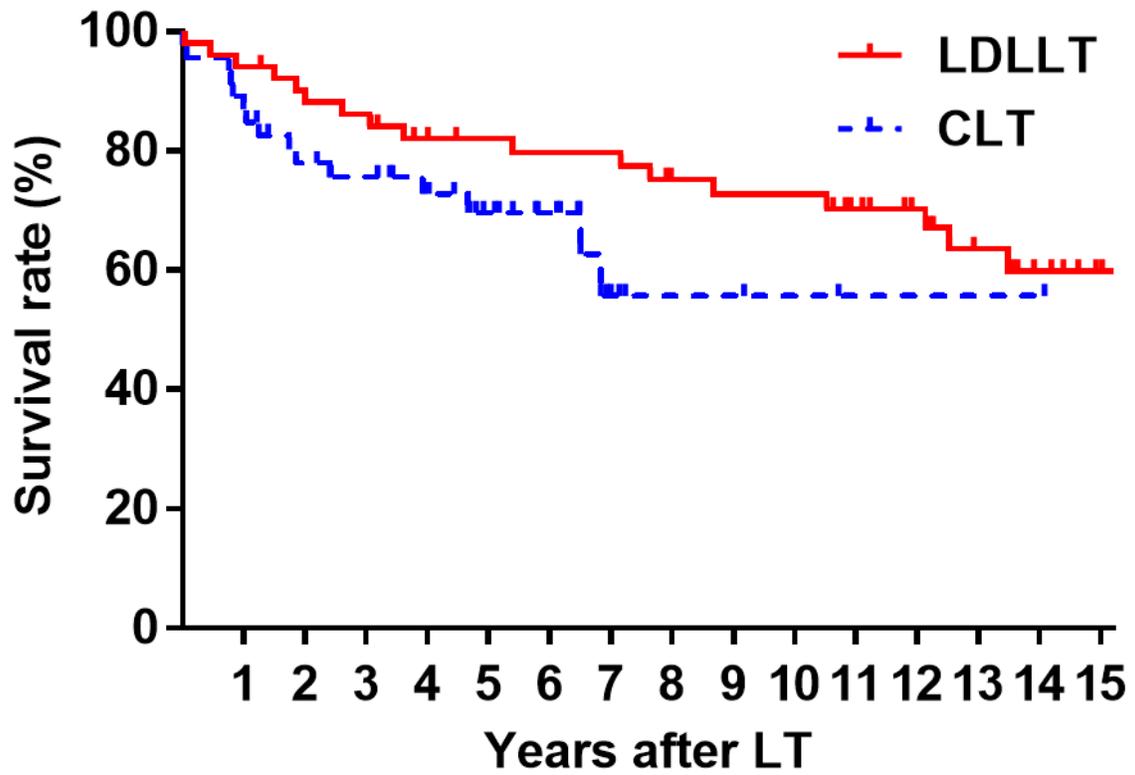


LDLLT	51	47	42	41	39	34	34	31	26	25	25	20	18	15	9	5
CLT	46	41	35	32	25	17	11	8	6	6	4	3	2	2	2	0

Number of patients at risk

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10





LDLLT	51	48	45	43	38	36	35	35	31	30	30	26	22	17	13	9
CLT	46	40	34	30	25	19	14	5	3	3	2	1	1	1	1	0
	Number of patients at risk															

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9

