Doxycycline use in patients with lymphangioleiomyomatosis: biomarkers and pulmonary function response*,**

Doxiciclina em pacientes com linfangioleiomiomatose: biomarcadores e resposta funcional pulmonar

Suzana Pinheiro Pimenta, Bruno Guedes Baldi, Ronaldo Adib Kairalla, Carlos Roberto Ribeiro Carvalho

Abstract

Objective: To assess blockade of matrix metalloproteinase (MMP)-2 and MMP-9, as well as the variation in FEV₁, in patients with lymphangioleiomyomatosis (LAM) treated with doxycycline (a known MMP inhibitor) for 12 months. Methods: An open-label, single-arm, interventional clinical trial in which LAM patients received doxycycline (100 mg/day) for 12 months. Patients underwent full pulmonary function testing, a six-minute walk test, and quality of life assessment, as well as blood and urine sampling for quantification of MMP-2, MMP-9, and VEGF-D levels—at baseline, as well as at 6 and 12 months after the initiation of doxycycline. Results:Thirty-one LAM patients received doxycycline for 12 months. Although there was effective blockade of urinary MMP-9 and serum MMP-2 after treatment, there were no significant differences between pre-and post-doxycycline serum levels of MMP-9 and VEGF-D. On the basis of their response to doxycycline (as determined by the variation in FEV₁), the patients were divided into two groups: the doxycycline-responder (doxy-R) group (n = 13); and the doxycycline-nonresponder (doxy-NR) group (n = 18). The patients with mild spirometric abnormalities responded better to doxycycline. The most common side effects were mild epigastric pain, nausea, and diarrhea. Conclusions: In patients with LAM, doxycycline treatment results in effective MMP blockade, as well as in improved lung function and quality of life in those with less severe disease. However, these benefits do not seem to be related to the MMP blockade, raising the hypothesis that there is a different mechanism of action.

Keywords: Lymphangioleiomyomatosis; Doxycycline; Matrix metalloproteinases; Respiratory function tests.

Resumo

Objetivo: Avaliar o bloqueio da metaloproteinase da matriz (MMP)-2 e da MMP-9 e a variação do VEF₁, em pacientes com linfangioleiomiomatose (LAM) após o uso de doxiciclina, um conhecido inibidor de MMP, durante 12 meses. Métodos: Ensaio clínico aberto de braço único no qual as pacientes com diagnóstico de LAM receberam doxiciclina (100 mg/dia) durante 12 meses. Elas foram submetidas à prova de função pulmonar completa, teste de caminhada de seis minutos, avaliação da qualidade de vida e coleta de amostras séricas e urinárias para dosagem de MMP-2, MMP-9 e VEGF-D antes do início do tratamento com doxiciclina e após 6 e 12 meses de tratamento. Resultados: Trinta e uma pacientes com LAM receberam doxiciclina durante 12 meses. Embora tenha havido um bloqueio efetivo da MMP-9 urinária e da MMP-2 sérica após o tratamento, os níveis séricos de MMP-9 e VEGF-D permaneceram estáveis. Com base na resposta à doxiciclina (determinada pela variação do VEF₁), as pacientes foram divididas em dois grupos: respondidas (doci-R; n = 13) e não respondidas (doci-NR; n = 18). As pacientes com alterações espirométricas leves apresentaram melhor resposta à doxiciclina. Os efeitos colaterais mais comuns foram epigastralgia, náusea e diarreia, todos de leve intensidade. Conclusões: Em pacientes com LAM, o tratamento com doxiciclina resulta em um bloqueio eficaz das MMP, além de melhorar a função pulmonar e a qualidade de vida daqueles com doença menos grave. No entanto, esses benefícios não parecem estar relacionados ao bloqueio das MMP, o que sugere um mecanismo de ação diferente.

Descritores: Lymphangioleiomyomatose; Doxiciclina; Metalloproteinases da matriz; Testes de função respiratória.

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Introduction

Lymphangioleiomyomatosis (LAM) is a rare disease that affects women of childbearing age. It can occur sporadically or in association with tuberous sclerosis complex (TSC), being characterized by lung cysts. The most common clinical manifestations of LAM are dyspnea and pneumothorax; other, less common, manifestations include hemoptysis, cough, and chylothorax. In patients with LAM, the most common abnormal pulmonary function test results are airflow obstruction and decreased DLCO. There is currently no curative treatment for LAM. Hormonal blockade is the most widely used treatment. However, there is a lack of evidence in this field. A retrospective study involving patients with LAM showed that the rates of decline in DLCO were significantly higher in those who were treated with progesterone. The results of small studies involving the use of gonadotropin-releasing hormone agonists have been controversial.

A randomized clinical trial showed that sirolimus, an inhibitor of the mammalian target of rapamycin pathway, can be useful in treating patients with moderately severe LAM-related lung disease. Recently, there has been interest in the possible role of matrix metalloproteinases (MMPs) in the pathogenesis of cystic lung destruction in LAM, including the possibility that MMPs represent a therapeutic target. It is known that MMPs are functional components of the extracellular matrix. They degrade a variety of matrix substrates and play an important role in lung remodeling and lymphangiogenesis. In addition, MMPs are inhibited by tissue inhibitors of metalloproteinases (TIMPs), which are indispensable in the regulation of MMPs. An imbalance between MMPs and their inhibitors has been implicated in the pathogenesis of lung diseases such as asthma, COPD, and Langerhans cell histiocytosis. Protease imbalance has been described in LAM lesions. A study examining lung biopsy samples from patients with LAM found elastic fiber degradation in areas of smooth muscle cell proliferation. Likewise, immunohistochemical analysis of lung biopsy samples from patients with LAM revealed increased immunoreactivity of MMP-2 and MMP-9, although not of TIMP-1 and TIMP-2, in the LAM cells when compared with that of those in normal lung cells. One case report showed an improvement in pulmonary function test results and a reduction in urinary MMP levels in an LAM patient who had severely impaired lung function and was treated with doxycycline, an MMP inhibitor. In a previous open-label trial, our group found a significant decrease in serum levels of MMP-2 in a cohort of LAM patients treated with doxycycline for 6 months.

The objective of the present study was to assess serum and urinary MMP-2 and MMP-9 levels in LAM patients treated with doxycycline for 12 months, as well as to assess the variation in FEV₁ in those patients.

Methods

This was an open-label, single-arm, interventional clinical trial. All LAM patients receiving outpatient treatment at the University of São Paulo School of Medicine Hospital das Clínicas Outpatient Clinic for Interstitial Diseases, located in the city of São Paulo, Brazil, were invited to participate in the study. The diagnosis of LAM was made in accordance with the European Respiratory Society guidelines. The study was approved by the local research ethics committee, and all participants gave written informed consent. One LAM patient had undergone lung transplantation and therefore was not enrolled in the trial.

At baseline, the patients underwent full pulmonary function testing, which was followed by a six-minute walk test (6MWT) and health-related quality of life assessment. Urine and blood samples were collected in order to determine the levels of MMP-2, MMP-9, and VEGF-D. After this initial evaluation, the patients were started on doxycycline at a dose of 100 mg/day, which was maintained for at least 12 months. All of the abovementioned tests were repeated at 6 and 12 months after treatment initiation.

The primary endpoints were MMP-2 and MMP-9 blockade, defined as decreased MMP-2 and MMP-9 levels, and the variation in FEV₁ after treatment with doxycycline for 12 months. The secondary endpoints were the variation in FVC, the variation in RV, and the variation in DLCO. We also evaluated the variation in the six-minute walk distance (6MWD), the variation in the minimum SpO₂ (as assessed during the 6MWT), and the variation in serum VEGF-D levels.

Urinary and serum MMP-2 and MMP-9 levels, as well as serum VEGF-D levels, were measured...
Results

Between 2006 and 2009, 41 patients with LAM were enrolled to receive doxycycline (100 mg/day). Of those 41 patients, 10 were lost to follow-up: 5 withdrew from the trial; 2 had worsening of the symptoms; and 3 had drug-related adverse events.

A total of 31 patients completed 12 months of doxycycline treatment (Appendix, section 2, Table A1). Mean age was 43 ± 8 years. In 29 patients, the diagnosis of LAM was based on histopathological features, whereas, in 2, the diagnosis was based on typical clinical and radiological features. The median time from the onset of symptoms to the diagnosis of LAM was 9 months (range, 6–24 months).

In the 31 patients, baseline pulmonary function was characterized by mild obstruction and slightly reduced DLCO (Table 1). After 12 months of doxycycline treatment, there was a significant mean decrease in FEV₁ (70 mL) but no significant variation in DLCO. The results of the 6MWT showed that there was an insignificant (25-m) increase in the mean 6MWD and a reduction in the minimum SpO₂. There was an improvement in some of the SF-36 physical and mental domain scores (Table 1).

As shown in Figure 1A, there was a significant reduction in urinary MMP-9 levels (from 10,487 pg/mL at baseline to 4,061 pg/mL after 12 months of treatment with doxycycline; p < 0.001). Serum MMP-2 was also blocked. However, there were no significant differences between pre- and post-treatment serum MMP-9 levels (Figure 1B), and urinary MMP-2 levels were undetectable. All MMP-related data are shown in Table 1.

Blood and urine samples were collected from 10 healthy women (controls), whose mean age was 40 ± 4 years (p = 0.29 vs. the mean age of the LAM patients).

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Blood and urine samples were collected from 10 healthy women (controls), whose mean age was 40 ± 4 years (p = 0.29 vs. the mean age of the LAM patients).

Median baseline serum and urinary MMP-9 levels were significantly higher in the LAM patients than in the healthy controls (933 vs. 89.6 ng/mL; p < 0.0001, and 10,487 vs. 200 pg/mL; p < 0.0001, respectively). Baseline serum and urinary MMP-2 levels were undetectable in the control group, with no significant differences between the controls and the LAM patients in terms of those levels.

Median baseline serum VEGF-D levels were significantly lower in the controls than in the LAM patients (185 vs. 821 pg/mL), in whom
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The functional parameters, SF-36 scores, MMP levels, and VEGF-D levels in the doxy-R and doxy-NR groups are shown in Tables 2 and 3. The patients in the doxy-NR group showed an obstructive pattern, with air trapping, whereas those in the doxy-R group did not. The median variation in FEV1 (in mL) from baseline to treatment month 12 was calculated. There was a median increase of 70 mL (range, 30-110 mL) in the

Table 1 - Pulmonary function test results, six-minute walk test results, biomarkers, and Medical Outcomes Study 36-item Short-form Health Survey scores at baseline and after 12 months of treatment with doxycycline in 31 patients with lymphangioleiomyomatosis.

| Variable | Result | p |
|----------|--------|---|
| Pulmonary function test | | |
| FVC, L | 3.17 ± 0.60 | 3.19 ± 0.60 | 0.792 |
| FVC, % of predicted | 92 ± 14 | 93 ± 14 | 0.751 |
| FEV1, L | 2.24 ± 0.70 | 2.17 ± 0.70 | 0.034 |
| FEV1, % of predicted | 79 ± 23 | 77 ± 25 | 0.042 |
| FEV1/FVC ratio | 0.70 ± 0.20 | 0.67 ± 0.20 | 0.003 |
| TLC, L | 5.03 ± 0.80 | 5.09 ± 0.70 | 0.408 |
| TLC, % of predicted | 103 ± 14 | 105 ± 14 | 0.393 |
| RV, L | 1.82 ± 0.60 | 1.91 ± 0.70 | 0.263 |
| RV, % of predicted | 130 ± 47 | 137 ± 52 | 0.282 |
| RV/TLC ratio | 0.36 ± 0.08 | 0.37 ± 0.10 | 0.295 |
| DLCO, mL/min/mmHg | 17.0 ± 6.8 | 16.76 ± 6.0 | 0.713 |
| DLCO, % of predicted | 65 ± 25 | 64 ± 22 | 0.745 |

Six-minute walk test

| Distance, m | 490 ± 109 | 515 ± 90 | 0.132 |
| Distance, % of predicted | 90 ± 20 | 95 ± 17 | 0.113 |
| Minimum SpO2, % | 94 (87-95) | 93 (84-95) | 0.202 |

Biomarkers

| Serum MMP-9, ng/mL | 933 (730-1,202) | 1,076 (809-1,367) | 0.140 |
| Urinary MMP-9, pg/mL | 10,487 (4,565-20,963) | 4,061 (712-9,985) | < 0.001 |
| Serum MMP-2, pg/mL | 0 (0-833) | 0 (0-179) | 0.005 |
| VEGF-D, pg/mL | 821 (407-2,113) | 913 (313-2,262) | 0.590 |

SF-36 domains

| Physical functioning | 70 (60-85) | 70 (50-88) | 0.465 |
| Role-physical | 50 (50-50) | 75 (25-100) | 0.054 |
| Bodily pain | 78 (56-95) | 70 (58-90) | 1.000 |
| General health | 75 (48-80) | 75 (58-80) | 0.717 |
| Vitality | 65 (53-80) | 65 (55-80) | 0.611 |
| Role-emotional | 100 (33-100) | 100 (67-100) | 0.147 |
| Mental health | 62 (52-84) | 80 (58-84) | 0.006 |
| Social functioning | 88 (56-94) | 88 (63-100) | 0.165 |

Minimum SpO2: minimum SpO2 sustained for 10 s; MMP: matrix metalloproteinase; and SF-36: Medical Outcomes Study 36-item Short-Form Health Survey. Values expressed as mean ± SD, except where otherwise indicated. One patient did not perform the six-minute walk test after the 12-month treatment. Values expressed as median (interquartile range).

serum VEGF-D levels remained stable over the course of doxycycline treatment (Figure 1C).

Although all 31 patients showed a decrease in mean FEV1 after doxycycline treatment, a subset of those patients showed an increase in or a stabilization of FEV1. The 31 patients were divided into two groups on the basis of the variation in FEV1 (from baseline to doxycycline treatment month 12): the doxycycline-responder (doxy-R) group, which comprised 13 patients with increased or stable FEV1; and the doxycycline-nonresponder (doxy-NR) group, which comprised 18 patients with decreased FEV1. (Figure 2A).

The functional parameters, SF-36 scores, MMP levels, and VEGF-D levels in the doxy-R and doxy-NR groups are shown in Tables 2 and 3. The patients in the doxy-NR group showed an obstructive pattern, with air trapping, whereas those in the doxy-R group did not. The median variation in FEV1 (in mL) from baseline to treatment month 12 was calculated. There was a median increase of 70 mL (range, 30-110 mL) in the
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Doxy-R group and a median decrease of $-140$ mL (range, $-260$ to $-110$) in the doxy-NR group. The median variation in FVC in both groups followed the same trend as that of the variation in FEV$_1$, with significant differences between the two groups ($p = 0.005$; Figure 2B). Functional impairment was greater in the doxy-NR group, as were MMP and VEGF-D levels (Tables 2 and 3).

After treatment with doxycycline, the patients in the doxy-R group showed an improvement in the SF-36 scores, the social functioning and role-physical domain scores being significantly higher. The patients in the doxy-NR group showed an improvement, although not significant, in the physical and mental domain scores. The SF-36 scores are shown in Tables 2 and 3.

In order to evaluate functional markers of response to doxycycline, we compared the doxy-R and doxy-NR groups before treatment initiation and found that the patients with less severe disease (lower TLC and milder obstruction) responded better to doxycycline (Appendix, section 2, Table A2). The ROC curve analysis showed that the FEV$_1$/FVC ratio that was most accurate in predicting the response to treatment with doxycycline was $0.71$ (area under the curve $= 0.690$; 95% CI: $0.50$-$0.88$; $p = 0.07$; Appendix, section 2, Figure A1, panel A).

Of the 31 patients enrolled in the trial, 22 had previously received some type of hormonal blockade therapy. However, there was no significant difference between the doxy-R and doxy-NR groups in terms of the prevalence of previous hormonal blockade therapy ($p = 0.696$; Appendix, section 2, Table A3).

Twenty patients continued to receive doxycycline for a median time of 18 months after the end of the study period. Regarding the variation in FEV$_1$, after the end of the study, the patients in the doxy-R group showed a slight
severe functional impairment and that doxycycline is safe for patients with LAM. One of the factors likely involved in cystic lung destruction in LAM is MMP overexpression. It is known that MMPs are enzymes that are capable of degrading collagen and elastin in the extracellular matrix of lung tissue.\(^{12}\) Chang et al. demonstrated the in vitro effect of doxycycline on TSC2-null cell adhesion, as well as on MMP-2 and MMP-9 expression, revealing a reduction in LAM cell proliferation, although high doses of doxycycline were required and there was no significant blockade of MMP expression.\(^{30}\) They also suggested that the antiproliferative effects of doxycycline are unlikely to be directly due to MMP inhibition, given that cell proliferation was not inhibited by ilomastat, a potent MMP inhibitor.\(^{30}\) Moir et al. demonstrated that doxycycline significantly reduced MMP-2 levels in LAM-derived cells and in TSC2-null mouse embryonic fibroblasts.\(^{31}\)

In the present study, doxycycline was found to induce effective MMP blockade, a finding reduction in \(\text{FEV}_1\), whereas those in the doxy-NR group showed a sizeable reduction, the variation in \(\text{FEV}_1\) after the end of the study having followed the same trend as that of the variation in \(\text{FEV}_1\) during the study period (Appendix, section 2, Figure A1, panel B).

The most common adverse events were epigastric pain (45%), nausea (19%), diarrhea (16%), and itching (6%). They were mild and self-limiting, specific treatment being rarely required. Of the 41 patients enrolled in the trial, 3 (7%) had adverse events requiring doxycycline discontinuation. Of those 3 patients, 1 had acute colitis, 1 had chronic diarrhea, and 1 had hemorrhoids.

**Discussion**

To the best of our knowledge, the present study is the first to demonstrate the effects of doxycycline, a known MMP inhibitor, on serum MMP levels, urinary MMP levels, and serum VEGF-D levels, as well as on pulmonary function test results and quality of life, in a cohort of LAM patients. The main findings of the present study include effective urinary MMP-9 and serum MMP-2 blockade induced by a 12-month treatment with doxycycline, without a significant influence on VEGF-D levels. We believe that treatment with doxycycline can be beneficial for patients with less severe functional impairment and that doxycycline is safe for patients with LAM.

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Doxycycline has been described as an MMP blocker in previous studies of other diseases, being able to suppress cerebral MMP-9 expression and angiogenesis in a mouse model and to reduce MMP-2 and MMP-9 levels to prevent thoracic aortic aneurysms.\(^{32,33}\)

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that corroborates our previous findings in a slightly larger cohort of patients. However, there was no association between MMP blockade and functional improvement. We also found a reduction in MMP levels in the doxy-R and doxy-NR groups, a finding that is suggestive of an MMP-independent mechanism of action for doxycycline. However, we tested only MMP-2 and MMP-9 and did not explore the possibility of involvement of other MMPs, such as MMP-1 and MMP-8, or the inhibition of TIMP activity, as previously described.

Serum VEGF-D levels remained stable after doxycycline treatment (Figure 1A). Although vascular permeability and angiogenesis inhibition have been reported to be induced by doxycycline, the pathway seems to be MMP-independent. Although median baseline VEGF-D levels were found to be higher in the patients in the doxy-NR group than in those in

### Table 2 - Pre- and post-doxycycline functional parameters, matrix metalloproteinase levels, VEGF-D levels, and Medical Outcomes Study 36-item Short-form Health Survey scores in the 13 lymphangioleiomyomatosis patients allocated to the doxycycline-responder group as determined by the variation in FEV₁.

| Variable                      | Doxy-R group | p       |
|-------------------------------|--------------|---------|
|                               | Pre-doxycycline | Post-doxycycline |       |
| Pulmonary function test       |              |         |       |
| FVC, L                        | 3.0 ± 0.3    | 3.2 ± 0.3 | 0.023 |
| FVC, % of predicted           | 90 ± 13      | 95 ± 12  | 0.026 |
| FEV₁, L                       | 2.31 ± 0.40  | 2.40 ± 0.40 | 0.003 |
| FEV₁, % of predicted          | 84 ± 14      | 86 ± 14  | 0.002 |
| FEV₁/FVC ratio                | 0.77 ± 0.10  | 0.76 ± 0.10 | 0.173 |
| TLC, L                        | 4.6 ± 0.5    | 4.8 ± 0.6 | 0.310 |
| TLC, % of predicted           | 98 ± 13      | 101 ± 15 | 0.327 |
| RV, L                         | 1.6 ± 0.5    | 1.6 ± 0.6 | 0.956 |
| RV, % of predicted            | 117 ± 43     | 118 ± 47 | 0.940 |
| RV/TLC ratio                  | 0.34 ± 0.08  | 0.33 ± 0.08 | 0.640 |
| DLCO, ml/min/mmHg             | 18.5 ± 6.0   | 18.0 ± 5.0 | 0.514 |
| DLCO, % of predicted          | 72 ± 20      | 70 ± 18  | 0.448 |
| Six-minute walk test          |              |         |       |
| Distance, m                   | 515 ± 66     | 523 ± 52 | 0.633 |
| Minimum SpO₂, %               | 94 (93-95)   | 94 (91-95) | 0.500 |
| Biomarkers                    |              |         |       |
| Serum MMP-9, ng/mL            | 837 (716-1,033) | 1,103 (773-1,237) | 0.328 |
| Urinary MMP-9, pg/mL          | 8,905 (5,607-21,829) | 6,735 (674-8,983) | 0.050 |
| Serum MMP-2, pg/mL            | 0 (0-182)    | 0 (0-40) | 0.144 |
| VEGF-D, pg/mL                 | 413 (277-2,113) | 328 (257-2,008) | 0.374 |
| SF-36 domains                 |              |         |       |
| Physical functioning          | 75 (65-85)   | 80 (75-95) | 0.281 |
| Role-physical                 | 50 (50-50)   | 100 (50-100) | 0.020 |
| Bodily pain                   | 57.5 (55-90) | 70 (55-77.5) | 1.000 |
| General health                | 80 (45-90)   | 75 (70-85) | 0.412 |
| Vitality                      | 70 (45-90)   | 70 (70-85) | 0.428 |
| Role-emotional                | 33 (33-100)  | 100 (33-100) | 0.158 |
| Mental health                 | 68 (40-84)   | 76 (52-88) | 0.051 |
| Social functioning            | 75.0 (50.0-88.5) | 87.5 (62.5-100) | 0.040 |

**Notes:** Doxy-R group: doxycycline-responder group; minimum SpO₂: minimum SpO₂ sustained for 10 s; MMP: matrix metalloproteinase; and SF-36: Medical Outcomes Study 36-item Short-form Health Survey. *Group of patients who responded to treatment with doxycycline, as evidenced by increased or stable FEV₁ at doxycycline treatment month 12 in comparison with FEV₁ at baseline. Values expressed as mean ± SD, except where otherwise indicated. Values expressed as median (interquartile range).
and Johnson & Tattersfield,\(^\text{(41)}\) i.e., 75 mL and 118 mL, respectively, the rate of decline in FEV\(_1\) in the present study was slightly lower, although we found that doxycycline had no impact on pulmonary function decline. The rate of DLCO decline in our patients was also lower than were those reported in the two studies cited above (0.69 and 0.90 mL/min/mmHg, respectively). In the present study, the patients in the doxy-R group showed no decline in FEV\(_1\), having shown the doxy-R group (995 ng/mL vs. 413 ng/mL), the difference was not significant (\(p = 0.325\)). These findings are concordant with those of previous studies that found no association between VEGF-D levels and lung function impairment.\(^\text{(38-40)}\)

After 12 months of treatment with doxycycline, we found a mean decrease of 70 mL in FEV\(_1\) and a mean decrease of 0.24 mL/min/mmHg in DLCO. In comparison with the annual rates of decline in FEV\(_1\), reported by Taveira et al.\(^\text{(8)}\) and Johnson & Tattersfield,\(^\text{(41)}\) i.e., 75 mL and 118 mL, respectively, the rate of decline in FEV\(_1\) in the present study was slightly lower, although we found that doxycycline had no impact on pulmonary function decline. The rate of DLCO decline in our patients was also lower than were those reported in the two studies cited above (0.69 and 0.90 mL/min/mmHg, respectively). In the present study, the patients in the doxy-R group showed no decline in FEV\(_1\), having shown

### Table 3 - Pre- and post-doxycycline functional parameters, matrix metalloproteinase levels, VEGF-D levels, and Medical Outcomes Study 36-item Short-form Health Survey scores in the 18 lymphangioleiomyomatosis patients allocated to the doxycycline-nonresponder group\(^a\) on the basis of their lack of response to doxycycline (as determined by the variation in FEV\(_1\)).\(^b\)

| Variable                  | Doxy-NR group | p       |
|---------------------------|---------------|---------|
|                           | Pre-doxycycline | Post-doxycycline |       |
| Pulmonary function test    |               |         |
| FVC, L                    | 3.2 ± 0.7     | 3.2 ± 0.7 | 0.114  |
| FVC, % of predicted       | 94 ± 15       | 91 ± 16  | 0.151  |
| FEV\(_1\), L              | 2.2 ± 0.9     | 2 ± 0.9  | <0.001 |
| FEV\(_1\), % of predicted | 75 ± 28       | 70 ± 28  | <0.001 |
| FEV\(_1\)/FVC ratio       | 0.65 ± 0.2    | 0.61 ± 0.2 | 0.009  |
| TLC, L                    | 5.3 ± 0.8     | 5.3 ± 0.7 | 0.922  |
| TLC, % of predicted       | 107 ± 13      | 107 ± 12 | 0.844  |
| RV, L                     | 2 ± 0.6       | 2.1 ± 0.7 | 0.129  |
| RV, % of predicted        | 140 ± 49      | 150 ± 54 | 0.155  |
| RV/TLC ratio              | 0.37 ± 0.08   | 0.4 ± 0.11 | 0.032  |
| DLCO, mL/min/mmHg         | 15.9 ± 7.5    | 15.8 ± 6.6 | 0.967  |
| DLCO, % of predicted      | 60 ± 27       | 60 ± 24  | 0.948  |
| Six-minute walk test      |               |         |
| Distance, m               | 472 ± 130     | 509 ± 112 | 0.119  |
| Minimum SpO\(_2\), %\(^c\) | 92.5 (83-95)  | 92 (78-95) | 0.087  |
| Biomarkers\(^c\)          |               |         |
| Serum MMP-9, ng/mL        | 1,011 (748-1,272) | 1,042 (809-1,307) | 0.756  |
| Urinary MMP-9, pg/mL      | 10,487 (4,526-15,653) | 3,970 (765-9,985) | 0.001  |
| Serum MMP-2, pg/mL        | 188 (0-905)   | 0 (0-214) | 0.017  |
| VEGF-D, pg/mL             | 995 (535-2,000) | 1,124 (810-2,262) | 0.211  |
| SF-36 domains\(^c\)       |               |         |
| Physical functioning      | 70 (51-84)    | 62.5 (46-81) | 0.084  |
| Role-physical             | 50 (50-50)    | 50 (25-100) | 0.668  |
| Bodily pain               | 79.0 (60.0-97.5) | 67.5 (57.5-90.0) | 0.821  |
| General health            | 70 (51-80)    | 67.5 (50-80) | 0.905  |
| Vitality                  | 63 (55-79)    | 65 (55-80) | 0.954  |
| Role-emotional            | 100 (33-100)  | 100 (67-100) | 0.426  |
| Mental health             | 66 (57-83)    | 80 (63-84) | 0.053  |
| Social functioning        | 87.5 (75.0-97.0) | 87.5 (62.5-97.0) | 1.000  |

Doxy-NR group: doxycycline-nonresponder group; minimum SpO\(_2\): minimum SpO\(_2\) sustained for 10 s; MMP: matrix metalloproteinase; and SF-36: Medical Outcomes Study 36-item Short-form Health Survey. \(^a\)Group of patients who did not respond to treatment with doxycycline, as evidenced by decreased FEV\(_1\) at doxycycline treatment month 12 in comparison with FEV\(_1\) at baseline. \(^b\)Values expressed as mean ± SD, except where otherwise indicated. \(^c\)Values expressed as median (interquartile range).
a slight but significant increase in FVC and FEV,
and stable SpO₂ during the 6MWT. However, the
doxy-NR group showed a decrease in FEV, and in
the FEV₁/FVC ratio, as well as showing an increase
in the RV/TLC ratio. By comparing the
doxy-R and doxy-NR groups (Appendix, section
2, Table A2), we found that doxycycline can be
beneficial for patients with mild spirometric
abnormalities. This finding was supported by the
ROC curve analysis, which showed that the FEV₁/
FVC ratio that was most accurate in predicting
the response to doxycycline was 0.71. In addition,
because the prevalence of hormonal blockade
was similar between the doxy-R and doxy-NR
groups, we hypothesized that hormonal therapy
has no influence on the response to doxycycline.

Twenty patients continued to receive
doxycycline after the end of the 12-month study
period. An evaluation performed after the end of
the study period revealed differences between the
two groups in terms of the rate of FEV₁ decline.
This finding suggests that doxycycline is more
effective in slowing functional impairment in
patients with LAM that is less severe (Appendix,
section 2, Figure A1, panel B).

The LAM patients investigated in the present
study underwent health-related quality of life
assessment before and after treatment with
doxycycline, an assessment that was not performed
in previous studies. We found an improvement
in some of the physical and mental domain
scores after treatment with doxycycline, a finding
that was more prominent in the patients in the
doxy-R group.

Doxycycline was found to be safe and well-
tolerated. The most common side effects were
those affecting the gastrointestinal tract and
were self-limiting.

Our study has some limitations. Because the
trial was not placebo-controlled, the fact that we
included patients with less severe forms of LAM
can be considered a bias, which could account
for the beneficial effect of doxycycline in the
doxy-R group patients, because those patients had
less functional impairment at baseline. Another
potential limitation is the fact that more than
10% of the patients enrolled in the trial were
lost to follow-up. In addition, we did not assess
MMPs other than MMP-2 and MMP-9, and we
did not assess TIMPs. Furthermore, we tested
doxycycline at only one dose level.

In summary, the present study showed that, in
patients with LAM, doxycycline treatment resulted
in effective MMP blockade. Doxycycline treatment
also resulted in improved or stable lung function
and in improved quality of life, particularly in the
LAM patients with mild spirometric abnormalities.
However, these benefits do not seem to be related
to the blockade of MMPs, which raises the
hypothesis of a different mechanism of action.
Because the lack of a placebo arm limits the
analysis of the clinical benefits of doxycycline,
randomized placebo-controlled studies are needed
in order to establish the actual role of doxycycline
in the treatment of patients with LAM.

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