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Continuous Positive Airway Pressure Thresholds for Nasolacrimal Air Regurgitation in a Cadaveric Model

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Abstract

Purpose—To elucidate the mechanisms underlying nasolacrimal air regurgitation (AR) in the setting of continuous positive airway pressure (CPAP) therapy.

Methods—Twelve nasolacrimal systems of 6 fresh female human cadavers were evaluated individually for AR using CPAP therapy before any nasolacrimal procedure. Cadavers were then randomly assigned to undergo NLD probing or endoscopic DCR and then each hemi-system was again evaluated for AR. The pressure where AR was first observed (discovery pressure) or maximum possible pressure in systems without AR was recorded. In systems that demonstrated AR, the pressure was then gradually decreased to the lowest pressure where regurgitation persisted. This pressure was recorded as the secondary threshold pressure.

Results—None of the 12 unoperated nasolacrimal systems or the 6 systems that underwent NLD probing demonstrated AR through the maximum CPAP therapy (30 cm H₂O). After endoscopic DCR, all 6 nasolacrimal systems demonstrated AR. The mean discovery pressure was 16.0 cm H₂O (range, 14.0–18.0 cm H₂O) and mean secondary threshold pressure was 7.25 cm H₂O (range, 6.5–8.0 cm H₂O).

Conclusions—Air regurgitation during CPAP therapy in the setting of prior endoscopic DCR can be replicated in a cadaver model. The secondary threshold pressures required for AR in this model were similar to AR pressures reported clinically. Prior to DCR, patients using CPAP therapy should be counseled on AR, and physicians should consider this phenomenon when evaluating ophthalmic complaints in postoperative patients on PAP therapy.

Introduction

Continuous positive airway pressure (CPAP) represents a mainstay of therapy for obstructive sleep apnea (OSA).¹ This therapy may produce several ophthalmic complications, including dry eyes, epiphora, and conjunctivitis, often from an ill-fitting mask leaking air.^{2, 3}

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Dacryocystorhinostomy (DCR), a common and effective treatment of nasolacrimal duct obstruction, bypasses the obstructed nasolacrimal duct via a new drainage passage. This passage also bypasses most of the structural and functional valves that may prevent retrograde flow of liquid and air (FIGURE 1). While the valve of Rosenmüller still factors into the passage of tears into the nose after DCR, its role in preventing reflux may be questionable.⁴

While air regurgitation through an unoperated nasolacrimal system in patients using CPAP occurs only rarely, it may occur after DCR in about 70% of cases.⁵⁻⁸ Regurgitation is associated with greater patency and higher success rate of DCR surgery.^{4, 9, 10} Associated symptoms, including difficulty sleeping, dry eyes, eye pain, and blurry vision, significantly disrupt CPAP compliance in up to 43-50% of patients.^{7, 8} Airway pressures causing air regurgitation have been reported for 7 patients and range from 7-10 cm H₂O, with a mean of 8.4 cm H₂O.⁷

A separate report describes AR in 4 patients after DCR or conjunctivo-DCR with glass Jones tube insertion using CPAP pressures that ranged from 8-10 cm H₂O.¹¹ Nasolacrimal AR with CPAP has been reported only rarely in patients without a history of DCR.^{5, 6} In these reports, pressures were given for 3 patients: two patients received CPAP at pressures of 17 and 15 cm H₂O, respectively, and one patient used bi-level positive airway pressure (BiPAP) at pressures of 18/10 cm H₂O. The present study aims to expand the current understanding of nasolacrimal AR with CPAP therapy by seeking to identify the threshold pressures for producing this phenomenon in a cadaver model before and after either nasolacrimal duct (NLD) probing or endoscopic DCR.

Methods

Cadaver Selection

Sixteen nasolacrimal systems of 8 fresh female human cadavers were evaluated for study inclusion. Cadavers were grossly evaluated for prior nasal surgery using a nasal endoscope and external scars in the nasolacrimal and upper respiratory system. Two cadavers were excluded due to recent tracheotomy surgery, and the other twelve nasolacrimal systems of 6 fresh female human cadavers were included for study. The study was performed adhering to the tenets of the Declaration of Helsinki.

Prior to DCR

With the cadaver in supine position, bilateral lateral canthal skin-muscle flaps were elevated with Stevens scissors and sutured with a simple running suture such that water applied to the medial canthus would immerse the lacrimal puncta (Figure 2A). A nasal positive airway pressure mask (FlexiFit407, Fisher & Paykel, Irvine, CA) was attached and a continuous seal around the nose was ensured. The mouth was manually held closed and covered with a damp surgical towel to prevent air leak. A bubbling model was used, similar to a previously described diagnostic test.^{5, 6}

Water was applied to the medial canthal area of one eye to immerse the lacrimal puncta. The contralateral lacrimal puncta were digitally occluded. A CPAP machine (Philips Respironics

System One Auto CPAP and Humidifier, Murrysville, PA, range of pressure 4-20 cm H₂O) was attached to the mask and turned on at the lowest pressure of 4 cm H₂O. The pressure was then gradually increased in increments of 1 cm H₂O per 10 seconds until bubbling was observed from the lacrimal puncta or maximum pressure was reached (FIGURE 2B). If AR was not observed at 20 cm H₂O (the maximal pressure of the CPAP machine), a BiPAP machine (Philips Respironics BiPAP S/T, Philips Healthcare, Murrysville, PA, range of pressure 8-30 cm H₂O) was attached to the nasal mask and turned on in continuous pressure mode at the lowest pressure of 8 cm H₂O. While observing the medial canthal area in question, airway pressure was gradually increased as described above until either bubbling was observed from the lacrimal puncta or the maximum possible pressure of 30 cm H₂O was reached. The procedure was repeated for the contralateral side.

Surgery Technique

For the cadavers assigned to NLD probing, this was carried out in standard fashion on first the right hemifaces followed by left hemifaces. The upper and lower puncta were dilated with a punctal dilator and then a #1 Bowman probe was passed and visualized under the inferior turbinate using an endoscope. NLD probing continued up to a #4 Bowman probe, confirming presence of the probe under the inferior turbinate with the endoscope each time. For the cadavers assigned to endoscopic DCR, the surgery was performed similarly to previous descriptions that involved a 1.5cm diameter osteotomy with preservation of the reflected nasal and lacrimal mucosa flaps.¹² DCR was performed on right hemifaces first, followed by left hemifaces. Nasolacrimal tubes were not placed.

After NLD Probing or endoscopic DCR

The nasal mask was attached and the medial canthal areas were prepared as described above. A CPAP machine (Philips Respironics System One Auto CPAP and Humidifier, Murrysville, PA) was attached and turned on at the lowest pressure of 4 cm H₂O. The pressure was then gradually increased in a method identical to that described above until bubbling was observed from the lacrimal puncta or maximum pressure was reached. This pressure was defined as the discovery pressure. If AR was not observed at 20 cm H₂O, then the BiPAP machine in continuous pressure mode was attached to the nasal mask at the lowest pressure of 8 cm H₂O and slowly titrated up as described above until either bubbling was observed from the lacrimal puncta or the maximum possible pressure of 30 cm H₂O was reached.

After reaching the discovery pressure, the pressure was gradually lowered until AR ceased. The pressure was then incrementally elevated until AR was noted again, and this pressure recorded. This pressure was defined as the secondary threshold pressure. After NLD probing or endoscopic DCR on the contralateral side, measurements were made while the punctae of the previously operated side were occluded with hemostats.

Results

Of the 12 naïve nasolacrimal systems included in the study, no AR was observed up to a maximum CPAP therapy pressure of 30 cm H₂O. Similarly, of the 6 systems that underwent NLD probing no AR was observed up to a maximum pressure of 30 cm H₂O. After

endoscopic DCR, all 6 nasolacrimal systems demonstrated AR. The mean discovery pressure was 16.0 cm H₂O (range, 14.0-18.0 cm H₂O) and mean secondary threshold pressure was 7.25 cm H₂O (range, 6.5-8.0 cm H₂O). (Table 1).

Discussion

While AR has been reported in 70-72% of cases using CPAP following DCR, the pressures that produced the regurgitation have been recorded for only a handful of cases. Further, these pressures were simply the pressures used by the patient, not the threshold/minimum pressure required to produce the phenomenon. The average pressure required to initially produce AR in the cadaver model of this study was 16 cm H₂O. This is higher than the average of about 8cm H₂O in the previously reported cases after surgery. Interestingly, after reaching the pressure required for AR, the pressure could then be reduced by about 50% in most cases to still allow for retrograde air flow. This secondary threshold pressure was much closer to previously reported clinical cases.

After DCR, the nasolacrimal system is no longer functionally closed to retrograde airflow because the ostium bypasses the higher resistance of the narrower bony nasolacrimal duct. What resistance is left after DCR is due only to soft tissue collapse of the canaliculi, punctae, and associated valves. The valve of Rosenmuller is thought to create a one-way valve to prevent reflux from the lacrimal sac into the canaliculi. However, after DCR surgery this valve may not prevent air regurgitation.⁴ CPAP therapy may initially dilate the canaliculi and punctae to lessen this resistance and allow for air regurgitation. Once air regurgitation occurs, it may more permanently affect the valves within the canaliculi to lower the threshold pressure to produce air reflux. This mechanism may account for both the lower secondary threshold pressures seen in our model and the values reported clinically in prior studies. Secondary threshold pressures in this model (range, 6.5-8.0 cm H₂O) were similar to pressures previously reported among patients after DCR in a prior study (range, 7-10 cm H₂O).⁷ The similarity in pressures between this study and clinical findings supports the accuracy of this cadaver model.

Conversely, postmortem changes in this cadaver model may introduce artifact to the system. Lack of Horner's muscle tone may allow for easier reflux. Also, a cadaver does not blink to allow the eyelid closure and therefore create resistance to AR. However, the secondary threshold being similar to the in vivo pressures described in the literature, suggest that our model is somewhat accurate. It is possible that clinically, the pressure that produces air reflux in CPAP patients after DCR decreases over time, so that patients may develop symptoms despite reducing the CPAP pressure. Interestingly, patients with a glass Jones tube required similar pressures as DCR patients to produce reflux, suggesting that the soft tissues over time offer almost no resistance to retrograde airflow and further suggest that the valve of Rosenmuller may not prevent AR.⁴

The occlusion of the contralateral system in this study may have impacted results. Measurements could have been performed without occlusion. The finding of no AR in unoperated system, however, shows that no reflux would have occurred and occlusion of operated systems was necessary to test the contralateral side. In this full body model, lung

compliance may have effected early pressures, but given that it was a closed system, should not affect the steady state pressures measured.

It may be possible that preserving the tenuous valve/soft tissue resistance could prevent air reflux from damaging those valves. For example, immediately minimizing CPAP pressure to the absolute lowest pressure required clinically may prevent the cycle of reflux and lower threshold pressures from occurring. Alternatively, a mechanical method of preventing air reflux before it occurs may allow for maintenance of some soft tissue/valve resistance to reflux.

In this study, we chose to use both a BiPAP machine in continuous pressure mode (pressure range 8-30 cm H₂O) and a CPAP machine (pressure range 4-20 cm H₂O) in order to test the entire range of continuous positive airway pressures commonly used. For patients with OSA, CPAP is a first-line therapy, and pressures commonly fall between 6-12 cm H₂O.⁸

In this study, all 6 unoperated nasolacrimal systems showed no AR at the highest testable level (30 cm H₂O), consistent with the rare occurrence of AR in CPAP patients with unoperated nasolacrimal systems.^{5, 6}

Interestingly, despite anecdotally having some patients with AR after probing clinically, AR was not observed after NLD probing in the cadavers tested. Probing enlarges the duct only slightly, which being longer and narrower than the DCR ostium should still provide significantly more resistance to air reflux. Also, in this cadaver model there may be greater collapse of soft tissue such as the canaliculi and lacrimal sac that may make AR less likely to occur. Last, all cadavers were female with narrower nasolacrimal ducts than males, providing more resistance to retrograde airflow.¹³ It is possible that male cadavers may have produced different results.

Nasolacrimal air regurgitation with CPAP after DCR can be replicated in a cadaver model with pressures similar to previously reported clinical cases. This model may elucidate the mechanisms that produce retrograde airflow, and it may help identify methods to prevent this complication from occurring.

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Figure 1.
Normal Nasolacrimal Drainage Anatomy

Figure 2.

A. Cadaver photo demonstrating elevation of a lateral canthal myocutaneous flap to allow for complete immersion of lacrimal puncta with water. **B.** Cadaver photo demonstrating air regurgitation via “water bubbling” model.

Positive airway pressure thresholds for nasolacrimal air regurgitation after DCR (cm H₂O)**Table 1**

	Cadaver 1		Cadaver 2		Cadaver 3	
	Right	Left	Right	Left	Right	Left
Discovery pressure (cm H ₂ O)	18.0	16.0	14.0	15.0	16.0	17.0
Secondary threshold pressure (cm H ₂ O)	8.0	7.5	6.5	7.5	6.5	7.5