ORIGINAL PAPERS

FITNESS TO DIVE; IMPLICATIONS OF CORNEAL SURGERY

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Abstract

Corrective surgery for myopia, and the wearing of contact lenses is becoming increasingly common. Potential and established divers, who are already certified, are presenting for dive medicals following procedures such as radial keratotomy and photorefractive keratectomy. The current literature about these procedures has been reviewed and general guidelines have been drawn up to aid in decision making about fitness to dive.

Introduction

As the appeal of recreational scuba diving continues to grow, those doing diving medical examinations are being presented with potential candidates who have undergone various new surgical procedures. The impact of these on the suitability of candidates to undertake scuba diving is not always appreciated by diving physicians, dive instructors or the candidates themselves.

Approximately 25% of the western world has some degree of myopia or short-sightedness. Measures to improve eye refraction for cosmetic, work or social reasons have increased dramatically over the past 10 years. From a greater understanding of the anatomy and physiology of the cornea various strategies have been developed to correct myopic eyes. These include contact lenses, radial keratotomy (RK) and photorefractive radial keratectomy (PRK). Other techniques currently under investigation include the implantation of an adjustable ring within the cornea which could reversibly alter corneal structure and implantable hydrogel corneal implants.[1]

This paper reviews the present position of contact lenses, radial keratotomy and photorefractive keratectomy with relevance to scuba diving.

Corneal Pathophysiology

Although the lens of the eye "fine tunes" changes in light refraction, the majority of refraction occurs at the cornea. While the total power of the eye to focus a distant object on the retina is about 60 diopters, the cornea accounts for approximately 45 diopters. Hence surgical procedures which alter corneal geometry and therefore correct refractive errors are currently being evaluated.

The human cornea is divided into 5 layers. These are; epithelium, Bowman's membrane, stroma, Descemet's membrane and endothelium. The mechanical strength comes from the stroma which accounts for 90% of the thickness of the cornea along with Bowmans membrane. This stroma comprises 300-500 sheets or lamellae of collagenous material, supported in a jelly-like ground substance, which lie parallel to each other.[2] The ocular clarity of the cornea depends on these collagen fibrils being of similar diameter and equal distribution. The adult cornea has a radius of curvature of 7.86 mm (SD 0.26 mm), a horizontal diameter of 11-12 mm and corneal thickness of around 0.52 mm at the centre to 0.65 mm at the periphery.

During some refractive correction procedures (e.g. RK) incisions are made in the cornea to induce flattening of the cornea and hence a change in refraction. The healing and refractive responses are biphasic; there is an instantaneous component due to acute visco-elastic changes, usually within one hour, followed by a slower progressive healing. The surgical correction changes refraction by approximately 25% during the healing process and this may take up to 4 years to complete.[2]

Contact Lenses

Contact lenses are becoming increasingly popular to correct refractive problems, especially in the workplace, military[3] and sporting worlds. The types of lenses currently available include; traditional hard, polymethylmethacrylate (PMMA) lenses; gas permeable silicone or cellulose acetate lenses; daily wear soft hydrogel lenses and extended wear soft hydrogel lenses.[4] The traditional hard lenses are infrequently used nowadays. Despite their good visual acuity, stability and resistance to deposit formation, they are uncomfortable and unsuitable for extended wear. Hard gas permeable lenses are more comfortable and are less prone to causing corneal damage, but are more expensive, more susceptible to damage and need more maintenance and care. Soft hydrogel lenses are the most comfortable to wear for prolonged periods of time and are more closely adherent to the eye. However they fail to correct vision as effectively as hard lenses, are more expensive and are prone to a greater number of complications. These include deposit formation and bacterial contamination.

Complications of contact lenses, in general, include mechanical damage (e.g. foreign body beneath lens, lens defect or incorrect positioning of lens), corneal hypoxia, alteration of eye flora and hypersensitivity. Corneal hypoxia occurs as a consequence of impaired tear flow and oxygen exchange. Subsequent lactate accumulation and metabolic pump failure lead to corneal overhydration and oedema formation. This may in turn cause corneal neovascularisation and lead to diminished visual acuity.

Conjunctivitis may be caused by infections or be non-infectious in aetiology. Corneal damage, especially ulceration, is the most worrisome complication of contact lens wear. Infectious aetiologies include careless cleaning techniques, extended wear or use in immunocompromised patients. *Pseudomonas* is recovered in up to two thirds of all cultutre positive corneal ulcers and may lead to permanent visual loss.[4] Other commonly isolated microorganisms include; *Staphylococcus Aureus, Serratia, Bacillus, Bacteroides, Fusobacterium* along with the difficult to eradicate *Acanthamoeba*.

Radial keratotomy

Although the use of surgical incisions to alter corneal curvature and treat astigmatism began in the late 19th century, effective corneal surgery was pioneered by Sato in Japan in 1953.[5] These earlier operations using posterior incisions were complicated by corneal oedema. The technique was modified to affect the anterior stroma only by the Russian, Fyodorov, in 1974[6] and introduced into the US in 1978[7] and subsequently into Australia in the early 1980's (personal communication Dr J Glastonbury).

The technique involves incising the cornea to produce flattening and subsequent refractive changes. The actual surgical technique varies greatly among surgeons, as do the instruments used. Generally surgeons can improve outcome by minimising the central clear zone, thus increasing corneal flattening, by optimising the number of incisions to between 4 and 8 and finally making the incision as deep as possible without causing micro- or macro-corneal perforation, again to increase flattening.[8]

Complications of radial keratotomy include temporary problems e.g. pain, glare, fluctuating vision[9] diurnal variation in vision, complications which reduce visual acuity e.g. under and overcorrection, astigmatism, epithelial inclusion cysts and finally those complications that potentially reduce visual function. These include, monocular diplopia, halo and glare especially at night, disruption of binocular vision and loss of fine depth perception. Traumatic rupture of the cornea at the incision sites has been reported as a delayed sequelae of RK.[10]

Photorefractive keratectomy (PRK)

The introduction of the argon-fluoride 193nm excited dimer (excimer) laser over the past 4 years has potentially revolutionised refractive surgery. Its use was first reported in humans in 1987, with the first reported correction in a sighted eye described in 1989.[11] Whereas in RK up to 90% of the corneal depth is cut, PRK can produce changes in focal length of up to 5 diopters by ablating less than 5% of the corneal thickness. Small segments of the cornea are sculptured to remodel it so that optimal refraction is gained. The laser delivery system is computer programmed to deliver the laser energy patterns to the central corneal axis, minimising the degree of surrounding tissue destruction while optimally reshaping the cornea. This also involves destruction of Bowman's layer, as well as involving the central visual axis. This can be carried out as an outpatient procedure under topical local anaesthesia, with an operating time of approximately two minutes per eye. The advantage of using ultraviolet radiation is that it can ablate tissue with minimal damage to surrounding tissues. Longer wavelengths than 193 nm have a tendency to produce greater penetration and tissue destruction plus the added problem of potential oncogenensis,[12] although this is minimised by the short duration of exposure.

Complications of PRK include postoperative pain for a few days while the epithelium regenerates, corneal haze and transient overcorrection. While the overcorrection tends to settle within a few months, the haze appears early and peaks at between two and three months before regressing. In a small proportion of cases the corneal scarring is more pronounced leading to a reduction of visual acuity. Other problems include the complications of the topical steroid treatment along with excessive glare and halo affected vision. Glare has been reported to be a problem in up to 25% of cases after one year.

Implications for diving

CONTACT LENSES

Contact lenses of both hard and soft types have limitations in the commercial diving environment. In a study performed on two navy divers subjected to dives to 45.5 metres for 40 minutes, visible bubbles were present behind the hard polymethylmethacrylate (PMMA) lenses.[13] Slit lamp examination revealed rounded confluent areas of corneal oedema at the sites of bubble formation. This was secondary to impaired tear flow and prevention of normal metabolic exchange between corneal epithelium and precorneal tear film. These effects were not seen with soft lenses nor PMMA lenses with a 0.4 mm central hole. Infection is another important factor to consider. *Pseudomonas* ear infections (otitis externa) are common in saturation dives especially below 100 m. In such an environment where adequate cleaning of lenses may be a problem, *pseudomonas* eye infections may cause destruction of the eye. In such circumstances, contact lenses are not recommended. In contrast soft contact lenses are to be recommended for recreational scuba divers. Although bubble formation has been reported following recreational dives in divers wearing hard lenses this does not seem to be a problem with soft lenses.[14] Moreover, while hard lenses can be easily lost in a flooded face mask, soft lenses possess much more adhesion. Lovsund measured the adhesion of contact lenses by glueing a suture thread to hard and soft lenses assessing the tensile force needed to pull the lens from the eye.[15] Soft lenses required considerable force to remove them and this increased with increasing salt content of the water. In contrast, hard lenses needed little force and were unaffected by water salinity. As part of the same study volunteers snorkelled keeping their eyes open and blinking frequently using hard and soft lenses. Hard lenses fell out within 60 seconds, whereas soft lenses stayed in place.

RADIAL KERATOTOMY

While some authorities currently recommend that scuba diving is contraindicated or limited in patients with previous RK, there is limited data to support this. Although RK has been introduced only recently to Australia, thousands of patients in North America and Europe have undergone this procedure. Anecdotally many experienced and novice divers have had RK with no reported problems. It is known that any corneal incision (e.g. RK, corneal transplantation and trauma) results in a scar which has a reduced tensile strength. However reports of rupture of previous RK incisions have tended to be direct, low-area, high-pressure, axial compression directly to the globe or periorbital area. Forstot reported 8 cases of trauma in 7 patients following RK, 2 weeks to 14 months postoperatively.[10] These were due to a direct blow from a tennis ball, soft ball, war game pellet, tyre lever and unspecified "severe trauma". The only RK incisions to open were those secondary to severe trauma, with incisions of between 95 and 100% of the corneal thickness. Other case reports have described delayed rupture seven and ten years postoperatively.[16,17] These again were associated with severe direct axial pressure. Animal studies, using rabbit eyes, have demonstrated that the compressive force needed to rupture a globe 90 days post-operatively was approximately half of that of control non-operated eyes.[18] Campos and colleagues compared the ocular integrity of non-operated, RK and PRK pig eyes exposed to lateral compression.[19] While all 10 RK eyes ruptured at a pressure of 280 mm Hg at the sites of incision, none of the PRK (12.6% stromal thickness) or control eyes ruptured. When higher compressive forces were used ruptures occurred at the scleral muscle insertions in the PRK and control groups. It was not until the PRK depth was increased to 40% (not clinically used) that rupture occurred at the operative site.

The above data tends to suggest that corneal rupture is rare following RK and requires severe direct axial trauma to cause incision dehiscence. Dive instruction may need to be modified to protect such candidates from causing corneal damage when performing skills such as no-mask swimming and mask removal and replacement e.g. allowing students to swim with a completely flooded mask, and taking the snorkel off the mask for mask replacement, minimising the chance of trauma by the snorkel on the affected eye. Candidates may also be recommended to wear swimming goggles when performing watermanship skills to avoid trauma from others while swimming. Pressure changes within the mask (mask squeeze) should be minimised by emphasising the need to equalise continuously through the nose on descent.

Other potential problems include the presence of fluctuating vision (i.e. is it worse at night, or every second day) along with the presence of "haloes" or glare. These may make certain aspects of diving inappropriate e.g. night, cave or wreck diving, where reading instruments and torch light may make seeing difficult. Transient changes in visual acuity may be seen following intraocular pressure changes within the mask. It has been shown that patients who have undergone RK and who are subjected to raised intraocular pressure have improvement in their visual acuity.[20] This reversible effect may be due to transient flattening of the cornea. This has obvious implications for multiple daily dives with short surface intervals. In this case corneal curvature may not revert to pre-dive proportions immediately following the dive. This may lead to diminished and fluctuating visual acuity during a multi-day dive trip. Finally it is of great value to know the date of the operation and the type of operation. While candidates may enquire as to when is the safest time to dive following a corneal procedure, the data is unhelpful. The corneal healing process is slow and often incomplete especially when micro or macroperforation has occurred during the surgical procedure. To this end any potential or active diver should discuss their procedure with the surgeon who actually performed their operation and specifically note the number of incisions, depth and incidence of perforation.

PHOTOREFRACTIVE KERATECTOMY.

Photorefractive surgery is still at an early stage in Australasia, with relatively few centres performing PRK. Recent work from the United Kingdom[21] and Sweden,[22] reviewing up to 18 months follow up in sighted eyes, would indicate that PRK reliably corrects low myopes, with few complications. Ophthalmologists are however still awaiting the long term results (5 and 10 year) of PRK, with relevance to stromal haze, regression of correction, long term effects of laser therapy on the cornea (i.e. possible mutagenesis) along with the theoretical objection to ablating the basement membrane of the cornea i.e. Bowman's membrane. However at this time, increasing numbers of ophthalmic surgeons are undertaking PRK in Australia. Moreover diving candidates may present to diving medical centres in Australasia from the United States or Europe with a history of PRK.

From the animal data it would seem that the PRK eye is not any more structurally weakened than the normal eye at normal, clinically used excision depths.[19] This is of relevance to potential mask barotrauma, and differs from RK procedures. As with RK however the potential for glare and halo vision require increased care in those areas where limited visibility and artificial light sources are used.

The United States Air Force may be considering the use of PRK in their pilots, who are at present allowed to use contact lenses.[23] PRK offers the potential advantage of reducing spectacle and lens incompatibility with military optical and protective equipment. As with aviators, the prolonged use of contact lenses is problematic in commercial and military divers involved in prolonged operations at depth.[24] The advent of PRK may obviate the problems of bubble formation behind lenses, corneal trauma and infection. The reports of large clinical series are awaited with interest.

Conclusions

New strategies for coping with myopia are currently being developed and refined. The initial results of RK and PRK are promising, yet it is too early to say whether there may be detrimental long term sequelae. Potential and established divers who have undergone these procedures need some guidance on the possible effects of scuba diving on their vision. At present it would appear that neither RK nor PRK are absolute contraindications to scuba diving. Extreme care over equalisation techniques and avoidance of direct trauma is of paramount importance, however, in divers who have had a previous RK.

Guidelines for the management of divers who have undergone corneal surgery include;

1 There is no evidence that PRK causes significant structural corneal weakness.
2 There is a theoretical possibility that mask barotrauma may cause globe rupture after RK, however this has not been documented following scuba diving. Many people who have had RK continue to dive without problems.
3 Novice and experienced divers, who have undergone RK, and instructors need to be informed about potential problems with RK and ways of avoiding them, e.g. by emphasising the prevention of mask squeeze and the avoidance of in-water skills which may lead to face trauma.
4 Discussion of the surgery with the ophthalmologist involved to determine the type and extent of corneal surgery, depth of incision and any complications, such as perforation during the procedure is recommended.
5 Informed discussion with the diver is required. The potential risks must be made available to the diver so that he or she can make an informed judgement whether to start, or continue, diving.

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PROVISIONAL REPORT ON AUSTRALIAN DIVING-RELATED DEATHS IN 1991

Douglas Walker

Summary

In 1991 two breath-hold diving related fatalities were identified from the Great Barrier Reef area. It is possible that other deaths occurred in other areas but were recorded as drowning without full identification of the details.

Fifteen scuba diving related fatalities were identified, although details are still unavailable about one case.

Not all of the fatalities were regarded as requiring a formal inquest though all were thoroughly investigated by the police on behalf of the appropriate Coroner.

Breath-hold divers

BH 91/1

A group visiting the Barrier Reef included a business man, his son (age 14), and a new employee. After a morning of fishing, then lunch, they were offered masks and snorkels and the opportunity to swim and observe the coral. The employee, the victim, declined an offer of fins on the grounds that he was a good swimmer. The boy swam near the victim for a time and heard him say he was feeling tired. They became separated and on his return the boy thought the victim was playing a game with him as he was floating motionless, face down. He realised something was seriously wrong after there were no response when he pushed him.

The unconscious man was brought back to the boat and CPR started. He was taken by helicopter to hospital but died there later from the effects of anoxic cerebral damage. No reason can be given for his silent surface drowning in calm water close to others as no other pathology was identified.

SEPARATION/SOLO. NEAR OTHERS. RAPID SILENT SURFACE DROWNING. CALM WATER. GOOD SWIMMER. HEALTH HISTORY UNKNOWN. ASPIRATED GASTRIC CONTENTS DURING RESUSCITATION. DEATH DELAYED BY CPR.

BH 91/2

Three friends went to the beach, one remained ashore while the other two entered the water. The buddy was wearing half a wet suit, the victim a full one. Although they probably intended to spear fish this was not directly stated.

The buddy separated from his friend and returned to shore when he was feeling cold. The victim chose to remain diving over a ledge. Both the swimmer and the friend on the beach could see the victim at this time but from the beach about 20 minutes later neither could see him and they began to feel alarmed. A shore search was not successful. The body was washed ashore next morning. Possibly the victim had been held beneath a ledge by water power and freed only after the tide changed. He had not ditched his weight belt. As there is no information about his breath-hold ability it cannot be known whether this is an example of post-hyperventilation blackout.

Autopsy confirmed the cause of death was drowning but there was significant (90%) atheromatous narrowing of the left coronary artery and this may have been significant, although no evidence of myocardial infarct was noted. There was no history of ill health.

BREATH-HOLD SPEAR FISHING. SEPARATION WHEN BUDDY BECAME COLD. SKILL UN-