Int J Legal Med (2012) 126:19–25
DOI 10.1007/s00414-011-0556-7

ORIGINAL ARTICLE

A study considering the force required for broken glass bottles to penetrate a skin simulant

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Received: 25 October 2010 / Accepted: 25 January 2011 /

Abstract Injuries and assaults related to alcohol consumption are a growing concern in many countries. In such cases, the use of impulsive weapons, an object from the immediate environment, such as a glass bottle, is not uncommon. This current study utilises a material testing system to measure the force required to push a broken glass bottle into a skin simulant with the displacement of the bottle into the skin simulant being recorded simultaneously, using a linear variable differential transformer (LVDT). From this data, load versus displacement plots were produced. Multi-detector computed tomography (MDCT) was also used to analyse bottle wall thickness to determine if a relationship could be found between force required for penetration and bottle wall thickness. The forces required for the penetration of the skin simulant ranged from 9.8 to 56.7 N. The range was found to be independent of bottle type with the variation in force for penetration being attributed to the varying fracture points, with some fractures presenting a sharper point on first contact with the skin. Although the dangers associated with the use of broken bottles as weapons is apparent, there is a paucity of information in this area in the current English literature, which this study has addressed. The results of this study also highlight the risks of attempting reconstructions of broken bottle stab events.

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Keywords Forensic · Glass · Bottle · Force · Assault · Stab · Computed tomography

Introduction

Injuries and assaults related to alcohol consumption are a growing concern in many countries. In such cases, the use of impulsive weapons, an object from the immediate environment, such as a glass bottle is not uncommon [1]. In the past, injuries of this type may have been primarily associated with licensed premises; but currently, a large amount of bottle-related injuries are occurring in streets and parks as a possible result of alcohol consumption by gangs of youths. This is particularly prevalent as most beers, wines and spirits are sold in glass bottles; the bottle neck of which can be used as an effective weapon. Typically, when a bottle is used in an assault, the neck of the bottle is used as a handle; the bottle is then used either intact as a club or broken as a cutting weapon [2]. In approximately 10% of all assaults resulting in treatment in the UK emergency units, glasses and bottles are used as weapons [3, 4]. Official UK estimates suggest that a form of glass is used as a weapon in between 3,400 and 5,400 offences per year [2]. A study of five UK emergency units, consisting of 1,380 patients attending due to glass injuries, found that 21% of patients had been assaulted by glass bottles [5].

One of the important considerations from a forensic perspective is to estimate how much force was required to make a particular injury. However, as with other forms of weapons, such as knives, this often relies on a subjective opinion proffered by a forensic practitioner. To our knowledge, there are no peer-reviewed papers specifically considering the assessment of the force used in relation to an injury caused by a broken bottle.

The aim of the research presented within this paper was to consider the force required for a broken glass bottle to penetrate a skin simulant. The novel data presented illustrates how difficult it is, compared to a knife, to provide an estimate of the forces involved due to the shape of broken glass as a weapon. It considers how glass bottles break and the form of the broken glass that may present as a weapon. In doing so, it provides a new classification for practitioners to use to describe the presenting end of broken bottles. This paper assists those who may be involved in the investigation of such cases to explain to, for example, a jury the engineering principles involved in injuries caused by broken bottles.

Materials and methods

A total of 25 glass bottles were examined in the study; 5 clear wine bottles (W1-5), 5 green wine bottles (G1-5), 5 clear beer bottles (M1-5), 5 green beer bottles (S1-5) and 5 green tonic wine bottles (B1-5). These bottles were arbitrarily chosen from a range of readily available bottle types, which were considered representative of types of bottles that have been used in glass bottle-related assaults. As broken glass assaults occur with empty bottles, the fluid within each bottle was discarded.

Prior to breaking each bottle, the wall thickness of each bottle was examined, using multi-detector computed tomography (MDCT). This was undertaken using a Toshiba Aquilion 64 detector scanner (Toshiba, Crawley, UK). Each scan was undertaken as a full-helical 0.6-sec scan using a 1.25 slice thickness, 120 kV and 100 mA with reconstructions at 1.25 mm. All images were stored in DICOM format and analysed using OsiriX version 3.7.1. (http://www.osirix-viewer.com last visited July 2010).

Each bottle was smashed in the same manner by holding the neck of the bottle and shattering it on the edge of a steel table. The table was marked to ensure the base of each bottle came into contact with the same part of the table on each occasion. After smashing, each bottle was imaged again using the same MDCT protocol.

Owing to ethical difficulties with acquiring human skin for research purposes, a skin simulant was used in this study. The literature supports that a combination of foam and silicone rubber offers reproducible results, which are comparable with those of human skin [6–14]. This combination provides a realistic elastic deformation response during penetration, i.e. it deflects in a similar manner to skin. An open-cell polyether foam with a foam hardness in the region of 125–155 N and a density of 23–28 kgm^{-2} was chosen for this study (Acoustafoam, Shropshire, England). This was covered by a layer of silicone rubber [7]. The silicone rubber used consisted of two parts mixed in a 1:10 ratio. One hundred fifty grams of the base (part B, transil 40) was mixed with 15 g of catalyst/curing agent (part A, transil 55) for between 3–5 min (Mouldlife, Newmarket, England). The mixture was then poured into a specifically designed mould and spread out evenly to make a thin uniform layer. A piece of polyether foam was placed on top of the mould before the final set to create a good bond between the skin and foam, and left to set for 24 h.

To measure the force required to result in a given displacement of the skin simulant, a material testing system was used (Hounsfield Test Equipment Ltd, UK) [12]. A material testing system can either be used in tension, to pull materials to failure, or in compression to test materials response to compression/indentation. In a material testing system, a moving crosshead is used to push or pull the material under test; combined with a load cell, which is used to determine the magnitude of the applied load. The displacement is obtained from either monitoring the crosshead speed or inferring displacement, or this can be done more accurately by using a LVDT giving an independent measurement of displacement. For each bottle, the force required pushing the broken bottle into the skin simulant, and the displacement of the bottle into the skin simulant was recorded simultaneously. For each bottle, an LVDT was used to record vertical displacement. From this data, load versus displacement plots were produced.

Similar experimental setups have been used previously in the literature in knife studies [15–17]. Prior to carrying out the bottle experiments, a small number of control experiments were carried out using knives. The resultant load-displacement curves, which were produced, show a characteristic step (Fig. 1). This step correlates with skin penetration, and thus, the maximum force for penetration can be determined.

Results

For broken glass bottles, the force versus displacement graphs, in contrast to that of knives, were found to have no single, clear load-displacement incursion for the majority of the bottles tested. We hypothesize that this can be attributed to the multiple points of contact at the edge of the broken bottle, which produces a surface with a combination of blunt and sharp points. Although each bottle was smashed in as reproducible a manner as possible, the fracture pattern for each bottle was different. This, in part, was considered to be partly dependent on the position of any labelling on the bottle. Figure 2 shows the typical fracture patterns that were observed. These were classified into (1) tulip, (2) bayonet and (3) extended shards [18]. Most of the bottles fell into one of the first two categories. In some cases where

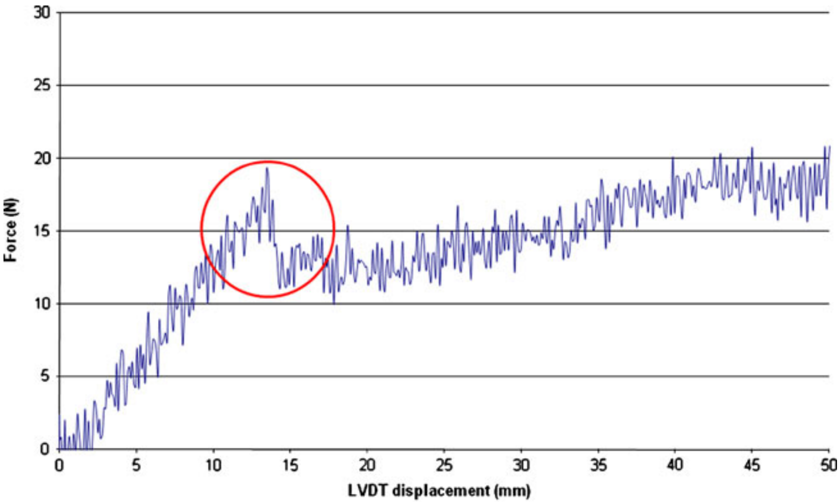


Fig. 1 Force-displacement curve for a knife. The *circle* highlights the characteristic step at the point of penetration

the bottle had one bayonet or two long, well-defined extended shards, the data could be more easily interpreted as these fracture patterns presented single or paired sharp points for skin penetration similar to that of the tip of a knife (Fig. 3).

To enable us to consider the maximum force required for penetration force versus displacement, graphs were produced using the graph software KaleidaGraph (version 4.02, Synergy Software, USA). In indentation processes, the load applied and resultant displacement into the sample during loading are related by a power-law function [19]. For conventional indentation with a controlled geometry of indenter, this can be expressed by the relationship $P = kd^n$, where P is the applied load, d is the displacement and n is an exponent that is determined by the properties of the material and the indenter geometry [20]. For geometries that are approximate to a cone shape, the exponent n is usually 2. Departures from the $P = kd^n$ relationship occur in cases where the material properties change, i.e. where the substrate influences the measured response, or where a coating/surface layer cracks. In the case here where we are dealing with a non-conventional geometry of indenter in terms of a fractured bottle, the first step in the analysis is to determine the value of the exponent n. This was achieved by fitting the load-displacement data (Fig. 4a) with a power-law function. The power-law fit can be seen in Fig. 4b. The power-law fit remains good, up until the point at which penetration of the skin occurs, and the mechanical response of the system changes as the properties are that of the underlying foam rather than the silicone skin. Similar strategies are used for detecting cracking in thin hard coatings [16, 17]. A straight line was then drawn on the graph showing displacement to the power n graph, where n is the experimentally determined exponent (as shown on Fig. 4c), and the first point where the curve deviated from the straight line was recorded as the penetration force (on Fig. 4c).

Fig. 2 Typical fracture patterns that were observed are shown (both as an image and an MDCT image) (1) tulip, (2) bayonet and (3) extended shards

Figure 5 illustrates the wide variations between the average penetration force for each bottle; whether the bottle was the same type of glass and/or shape or not. This variation is attributed to the complex geometry of the 'stabbing surface' of each bottle produced during the smashing of the glass, which allows multiple points of contact with the surface. The wall thickness of each bottle was measured in millimetres using OsiriX (Table 1). Table 1 and Fig. 5. illustrate that there is no obvious relationship between bottle thickness and the force required for penetration.

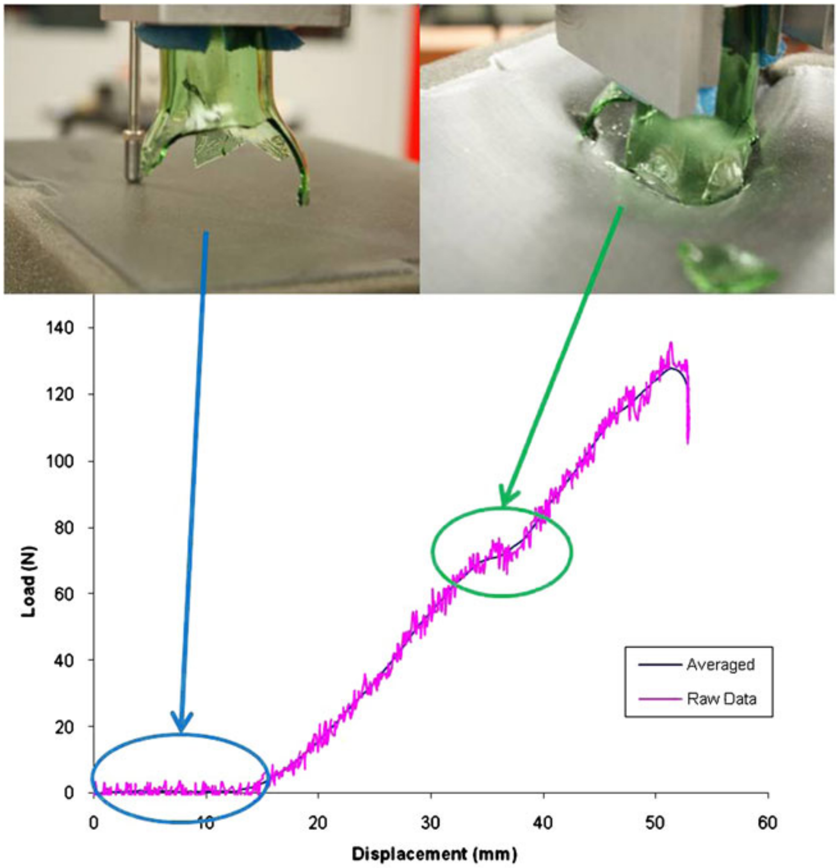


Fig. 3 A 'bayonet' type bottle producing a step in the load-displacement curve, which is more characteristic of knives

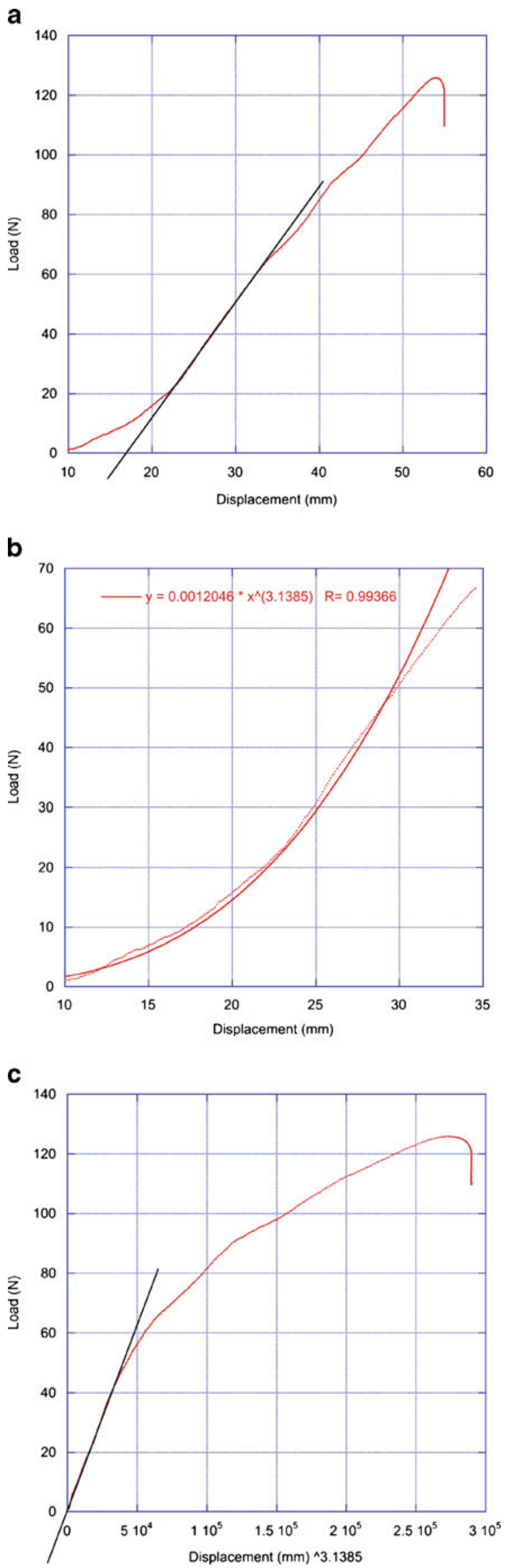
Discussion

Typically, when a bottle is used as a weapon in an assault, the neck of the bottle is used as a handle; the bottle is then used either intact as a club or is broken and used as a cutting weapon [2]. In cases where the bottle is used as a club, as long as the bottle remains intact, it will produce blunt trauma injuries, most commonly, lacerations. Blunt trauma to the head may produce skull fractures [18]. The presenting end of broken glass bottles produce incised wounds and cause the most life-threatening injuries [21].

Bolliger et al. studied the breaking energy to fracture glass beer bottles [22]. They found that full bottles, fractured at lower energies than empty ones, which is unsurprising as beer is commonly pressured at approximately 100–140 kPa [23]. In terms of the stress required to simply fracture bottles therefore, the pre-existing pressure would decrease the energy required for fracture [24]. This is well known in the glass industry, which uses bottles with greater wall thickness for carbonated drinks and has been one of the drivers for the move to polyethylene terephthalate (PET) bottles since the transportation costs and environmental impact decrease owing to the lighter weight PET containers [25]. Bolliger et al. concluded that empty bottles were sturdier than full ones [22]. However, both full and empty bottles have the same 'sturdiness'. What is different is that full bottles fracture at lower applied stresses than empty ones because of the pressurisation. Thus, it should not be interpreted that empty bottles could inflict greater damage when used as a weapon. The criteria for whether or not a bottle can fracture the skull depend on whether the energy for fracture of the bone is exceeded or not. Typically for a skull fracture the impact energy has to be greater than 45–101 J [26]. Impact energy is derived by the formulae;

$$\text{Kinetic energy} = 1/2 \text{ mass velocity}^2$$

In an experimental environment, velocity of attack can be kept constant. The difference in mass between an empty and full bottle becomes the determinate factor for the calculation of the impact energy. In reality, however, the assailant's ability to repeatedly swing a bottle of a fixed mass with the same velocity is unrealistic, and thus, the energy created will vary with each swing, and the injury sustained will be different on each impact. In both considerations, however, the increased mass of a full bottle will yield a greater likelihood of generating more energy than an empty bottle. Whether or not the bottle fractures in the attack is unimportant, as it is the transfer of energy that determines the level of injury.



◀ **Fig. 4** For a glass bottle, the force required for penetration of the skin simulant required the production of **a** standard load vs. displacement curve; followed by the calculation of a **b** power-law fit curve; and finally the production of a **c** load vs. displacement to the power *n* graph

A number of researchers have shown that broken bottles are commonly used as slashing or stabbing implements [2, 21, 27]. One of the key questions to consider is how much force is required to inflict injury with glass weapons. To our knowledge, this question has not been addressed within the literature to date. Previous studies considering penetration forces for knives, established that the sharpness of the knife is the key factor in determining the amount of force required for penetration [9, 15, 17, 28, 29]. Hainsworth et al. [9], reported that it is the tip radius, which defines the sharpness of a knife, i.e. the smaller the tip radius, the sharper the knife, and thus, the smaller the force required for penetration.

Prior to the study here, it may have seemed reasonable to assume that the thicker the bottle wall, the larger the tip surface that would be produced following the breaking of the bottle and ultimately the larger the penetration force; this, however, is not the case. We have identified that the fracture pattern, as a result of shattering, produces an almost unique ‘stabbing surface’ for each bottle regardless of type of glass, bottle shape or wall thickness. A complex fracture surface is present on the ‘stabbing surface’ containing a mixture of sharp and blunt tips of varying radii. This variation in the ‘stabbing surface’ for each bottle means that the penetration force also varies widely. Thus, it is not possible to predict a definitive value for the amount of force involved to cause a penetrating injury in a broken bottle attack. What it is possible to say is that although some bottles have similar penetration forces to knives, due to the presenting broken glass geometry, most require a much larger amount of force, which suggests that the majority of stabbing incidents involving bottles would tend to involve more energy than those involving knives. The authors would suggest, however, great caution to those in the field who would try to reconstruct a bottle-stab event. Due to the uniqueness of the ‘stabbing surface’, reconstructions could lead to a misleading value for penetration force.

It is common knowledge that broken glass bottles can be used as an effective penetrating weapon and the results of this study have reaffirmed this. The inherent risk associated with broken glass has resulted in the banning of such glassware in nightclubs of some cities, such as Glasgow, Scotland [30]. The study by Forsyth highlights the positive effects of using plastic rather than glass for serving alcoholic drinks and the reduced severity of alcohol-related assaults [30]. Our study provides the first set of

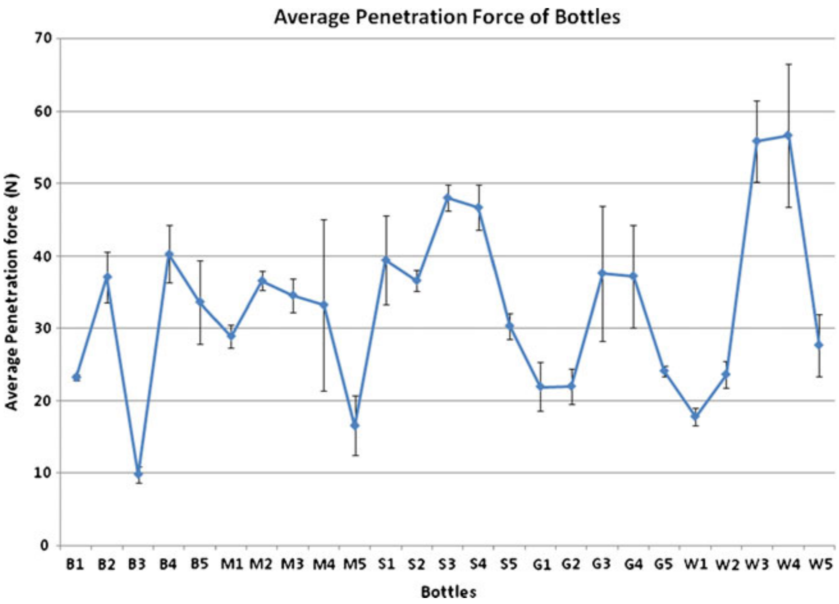


Fig. 5 The average force required for penetration of the skin simulant for each bottle

penetration force data for broken glass bottles and illustrates how the consideration of proffering an opinion on force used is different to that of knives. It presents a basic classification for the presenting end of the glass bottle, which is important when passing an opinion on force used and makes the observation of the risks associated with trying to replicate incidents involving broken bottles. Work continues in this area by the study group who are developing a new piece of scientific equipment to investigate and offer more data on penetration forces for stabbing events by different weapons in future.

Conclusions

A series of penetration tests have been carried using a material testing system to measure the force required to push a broken glass bottle into a skin simulant with the displacement of the bottle into the skin simulant being recorded simultaneously using a LVDT. From this data, load versus displacement plots were produced. MDCT was also used to analyse bottle wall thickness to determine if a relationship could be found between force required for penetration and bottle wall thickness. The findings of which, are summarised below.

- Typically, when a bottle is used as a weapon in an assault, the neck of the bottle is used as a handle.
- Typical fracture patterns that were observed were classified into (1) tulip, (2) bayonet and (3) extended shards (Fig. 2). Most of the fracture patterns fell into one of the first two categories.
- Unlike that of knives, the load-displacement graphs produced for bottles do not contain a characteristic step at the point of penetration and so required interpretation using graphical software. We hypothesize that this can be attributed to the multiple points of contact at the edge of the broken bottle, which produces a surface with a combination of blunt and sharp points.
- The smashing of bottles to give a stabbing instrument produces a unique 'stabbing surface' for each bottle, which means it is not possible to predict a definitive value for the amount of force involved to cause a penetrating injury in a broken bottle attack.
- Although some bottles have similar penetration forces to knives, due to the presenting broken glass geometry,

Table 1 The minimal, maximal and average thickness of the wall in millimetres for each glass bottle type

Bottle type	Minimal thickness (mm)	Maximal thickness (mm)	Average thickness (mm)
Clear wine (W1-5)	1.78	5.20	3.48
Green wine (G1-5)	1.98	4.70	3.28
Clear beer (M1-5)	2.05	3.61	2.83
Green beer (S1-5)	1.74	3.48	2.52
Green tonic wine (B1-5)	2.02	4.15	2.95

most require a much larger amount of force, which suggests that the majority of stabbing incidents, involving bottles, would tend to involve more energy than those involving knives.

- Great caution is suggested to those in the field who would try to reconstruct a bottle-stab event due to the uniqueness of the 'stabbing surface' reconstructions could lead to a misleading value for penetration force.

Acknowledgements Ms. C. Robinson, Mr. B. Kirkland, Mr. G. Clark and Ms. A. Brough are thanked for their technical assistance with the experimentation.

Conflict of interest None.

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