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HISTORICAL NOTE

The story of the gauge

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Summary

Gauges are old measures of thickness. They originated in the British iron wire industry at a time when there was no universal unit of thickness. The sizes of the gauge numbers were the result of the process of wire-drawing and the nature of iron as a substance. Gauges were measured and described in fractions of an inch during the 19th century. In the UK, one gauge was standardised and legally enforced as the Standard Wire Gauge. One important reason for the standardisation of the gauge was the convenience of craftsmen. In the 20th century, the gauge was to be replaced with the introduction of the International System of Units. However, within the field of anaesthesia at the threshold of the 21st century, the gauge seems hard to remove from the minds of craftsmen like anaesthetists.

Keywords Gauge, history, needle size.

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At some point in his or her career, every anaesthetist will have wondered about the meaning of the term 'gauge', often abbreviated as 'G' or 'ga' on needle packages and in scientific literature. How many inches are there in one gauge? Why does the gauge number increase as the needle gets thinner? Why is 28G not twice or half 14G? Shouldn't the gauge be abandoned and replaced by inches or millimetres, which are also mentioned on the needle packages? Answers to these questions were sought in linguistic, industrial, historical and legislative research.

Linguistic research

The noun 'gauge' is derived from and related to the French word 'jauge', meaning 'result of measurement' and this word is mentioned in 13th century documents. The principal meaning is 'a standard measure of weight or size to which objects can be compared' [1, 2]. In American orthography it is spelt 'gage'. The word is pronounced as 'geidz' (g as in 'get', ei as in 'table', d as in 'day' and z as 'si' in 'occasion'). In itself, a gauge is not a unit of length like an inch, a millimetre or a foot. It is a comparative standard, a defined set of sizes or thicknesses. There appear to be about 55 different gauges, including Twist Drill & Steel Wire Gauge for drill rod, English Music Wire Gauge, National Wire Gauge for steel wire, Standard Wire Gauge, Stitching Wire Gauge, Stubs Iron Wire Gauge, Warrington Wire Gauge, Yorkshire Wire Gauge and 28 different Birmingham Wire Gauges [3]. All these gauges differ more or less in range, size and inclination or declination with higher gauge numbers. There are also letter gauges, using letters instead of numbers. One US gauge for sheet metal is based on the weight of the sheet, not on the thickness. In most cases, a higher gauge number means smaller size, but music wire is the other way around [3]. Charles Holtzapffel, a 19th century civil engineer, lamented: 'There is little analogy, but great confusion because of all the existing gauges' [4].

It appears likely that the gauge numbers, and their equivalent in inches or millimetres as mentioned on needle packages, are either the Holtzapffel and Stubs Wire Gauge, adopted from the UK by the USA as the US Birmingham Wire Gage, or the British Standard Wire Gauge. Their equivalents in inches are displayed in Table 1. However, it should be mentioned that the notation on the packages is not accurate enough (in part because of conversion to millimetres) to distinguish between the differences of thousandths of an inch that allow differentiation between the various gauges.

Another size that is used on needle and catheter packages is the French Gauge or size, abbreviated as 'F' or 'Fr'. The French Gauge is a synonym for Charrière.

One French Gauge or Charrière equals 1/3 of a millimetre. Because this French Gauge does not have a specific range of sizes but follows the metric scale, it is not discussed in this review.

Industrial research

As the names of most gauges suggest, the gauge is closely related to the iron, steel and in particular, the wire-drawing industry. The practice of wire-drawing has existed for many centuries. Finds dating from ancient times indicate its existence. In Germany, wire-drawing is known to have occurred in the neighbourhood of Nuremberg in 1200. The process is shown and accurately described in the Deutsches Drahtmuseum in Altena, Germany. In England, the practice is found as early as 1435 in the neighbourhood of Coventry [5]. A thorough description is found in the book *History of Wiredrawing* by Reginald Charles Dudley Isgar, secretary of the Iron and Steel Wire Manufacturers Association of Great Britain in 1936. The process was as simple as it was ingenious. An iron plate was cut into strips, which were rolled and hammered into rods. The rod was drawn through a conical hole in a hardened draw-plate, die or gauge [6]. After intermediate annealing, the resulting wire could be drawn through the next, narrower, hole in the draw-plate to produce a thinner wire, and so on (Fig. 1). Each successive hole represented the utmost extension, and thereby reduction, of the wire diameter without breaking. Every manufacturer had his own draw-plate and gauge. This gauge represented the wire sizes he could deliver. Usually, he had a test wire gauge for his customers to check if the size was suitable for their purpose (Fig. 2). So, a wire gauge was not originally made to a measurement such as fractions of an inch, but was simply used to indicate the amount by which iron wire could be reduced by each draw or hole [7]. Although no two gauges are exactly the same, there exists some similarity between different gauges. Studies of an important group of wire gauges from Birmingham reveal that they all have more or less the same sizes. This can not be accidental. It is a function of the property of iron when it is drawn through a draw-plate. Josiah Latimer Clark (1822–1898), a civil engineer, was the first to note that in the Birmingham Wire Gauges, wire with each successive gauge number was ≈11% thinner than the preceding number [8].

Historical research

The need for standardisation

The need for, and the declaration of, standards goes back to ancient times. Standards for weights of wine and grain were mentioned in the Magna Carta in 1215. King

Table 1 Sizes of gauges in 1/1000 in.

Gauge no.	Holtzapffel and Stubs Gauge, 1847	Wire Gauge Committee, 1881	British Standard Wire Gauge, 1883
7/0			500
6/0			464
5/0			432
4/0	454		400
3/0	425		372
2/0	380		348
0	340		324
1	300	300	300
2	284	280	276
3	259	260	252
4	238	240	232
5	220	220	212
6	203	200	192
7	180	180	176
8	165	164	160
9	148	148	144
10	134	132	128
11	120	120	116
12	109	108	104
13	95	96	92
14	83	84	80
15	72	72	72
16	65	64	64
17	58	56	56
18	49	48	48
19	42	40	40
20	35	36	36
21	32	32	32
22	28	28	28
23	25	24	24
24	22	22	22
25	20	20	20
26	18	18	18
27	16	16	16,4
28	14	14	14,8
29	13	13	13,6
30	12	12	12,4
31	10	11	11,6
32	9	10	10,8
33	8	9	10
34	7	8	9,2
35	5	7	8,4
36	4	6	7,6
37		5	6,8
38		4	6
39		3	5,2
40		2	4,8
41		1	4,4
42			4
43			3,6
44			3,2
45			2,8
46			2,4
47			2
48			1,6
49			1,2
50			1

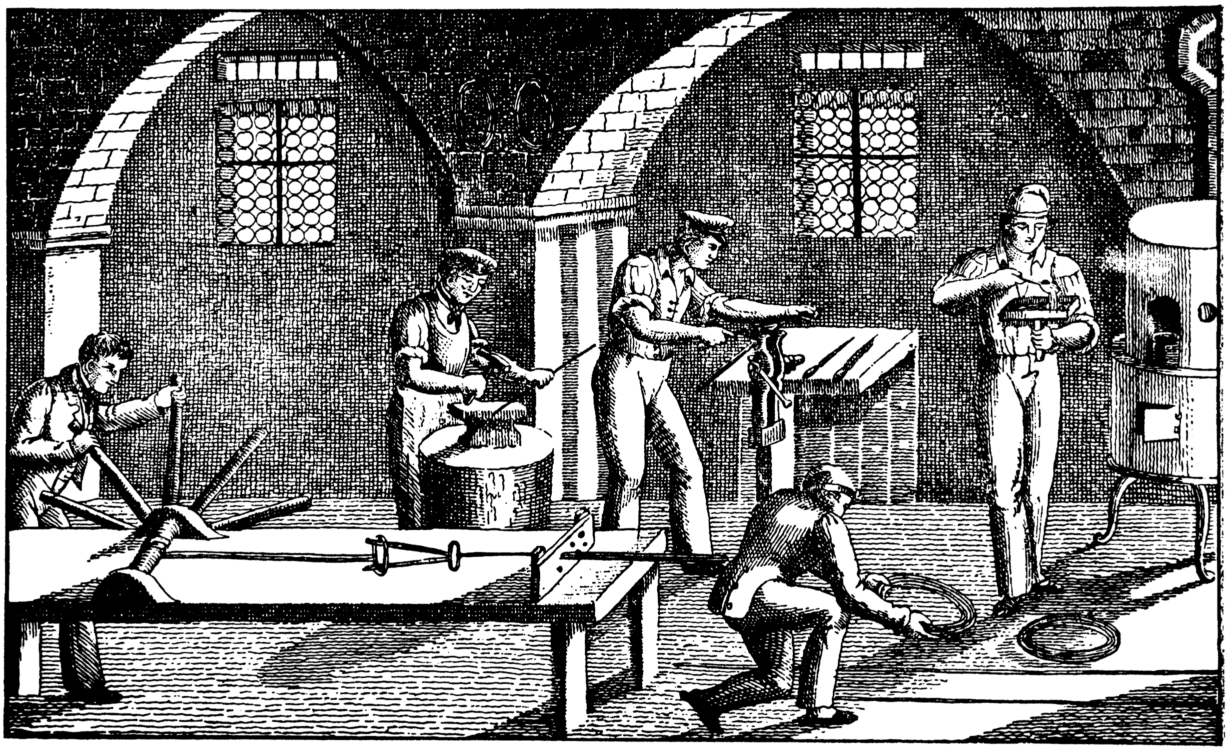

Figure 1 Draw-bench in the 18th century. From *History of Wiredrawing* by R.C.D. Isgar [6].

Edward I ordered in 1303: 'Throughout all our kingdom there be one weight and one measure, and that they be marked with the mark of our standard' [9]. This resulted in the Imperial Standard Yard, kept by the Exchequer in the Palace of Westminster, London.

At the end of the 18th century during the French Revolution, the foundations were laid for the International System of Units of length (the metre) and weight (the kilogram). This was to put an end to all the different local, regional and national measures and weights. There was to be one unit for every physical entity to be used by everybody (equality and fraternity at its finest!). Besides France, other industrial countries such as Germany and the USA gradually adopted this idea. The USA had been the first to adopt uniform sizes from the 1880s onwards. US presidents Washington and Jefferson advocated the use of the metric system rather than the inherited British measures. Mr T. C. Mendenhall, US superintendent of weights and measures, decided in 1893, with the approval of the Secretary of the Treasury, that the metre and the kilogram were the standards [10]. All accepted the metric and decimal system and abandoned gauges or made them secondary to the metric system.

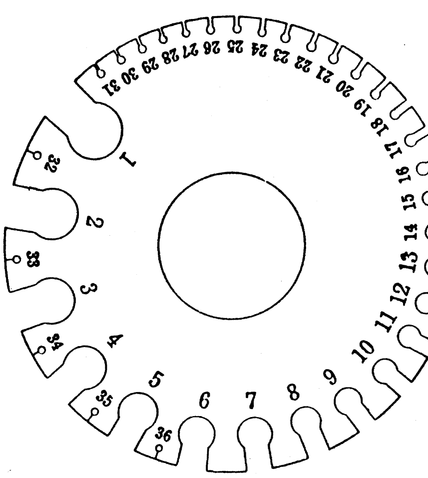

Figure 2 Wire gauge. From *Gauges and Fine Measurements* by F. H. Rolt [20].

Great Britain, the workshop of the world with its long industrial history, refused at first to adopt the metric system and maintained the imperial yard and the pound as standards. Besides them, many local measures like gauges were used. The only standardisation consisted of local agreements in guilds or industrial centres to use the same measures. The Birmingham Wire Gauge and Stubs Wire Gauge are examples of this informal standardisation. However, during the 19th century, two developments forced the gauge to a 'showdown'.

~~Suggested~~ Scale of Sizes of Standard Wire Gauge — 10 Aug

Denomination of Standard Number.	Equivalent in Imperial Measure Inch.	Denomination of Standard Number	Equivalent in Imperial Measure Inch.
No 8/0	0·5~~00~~35 in:	No. 22	0·028 in:
7/0	~~470~~ 500	23	24
6/0	4~~40~~69	24	22
5/0	~~415~~ 438	25	20
4/0	~~390~~ 406	26	18
3/0	~~365~~ 375	27	16
2/0	34~~8~~4	28	14
1/0	32~~8~~5	29	13
1	300	30	12
2	2~~80~~75	31	11
3	2~~60~~50	32	10
4	2~~40~~30	33	0·0090
5	2~~20~~10	34	80
6	~~200~~ 190	35	70
7	170 1~~80~~75	36	65
8	155 16~~4~~0	37	60
9	140 14~~8~~5	38	55
10	125 13~~8~~0	39	50
11	110 1~~20~~15	40	45
12	10~~8~~0	41	40
13	0·09~~8~~0	42	35
14	8~~4~~0	43	30
15	70 ~~72~~	44	25
16	62 64	45	0·00225
17	55 ~~56~~	46	200
18	48	47	175
19	42 ~~40~~	48	150
20	36	49	125
21	32	50	100

In accordance with suggestions made by the Birmingham and Yorkshire districts, the "Equivalents" would also be expressed in $\frac{1}{8}$ $\frac{1}{16}$ $\frac{1}{4}$ $\frac{1}{2}$ inch, and in mils, as well as in millimetres!

Figure 3 Suggested scale of sizes of standard wire gauge. Copied from a Board of Trade document (BT 101, Standard Wire Gauge Abstract of Replies, 1882). Crown copyright material in the Public Record Office is reproduced by permission of the Controller of Her Majesty's Stationery Office [21].

Instruments became available that were able to measure very small thickness and hence gauges. There was already the nonius, an auxiliary scale that enabled readings to be made to one-tenth of the division on the main scale. In 1830, Sir Joseph Whitworth (1803–1887), a British mechanical engineer, developed a measuring instrument able to measure to an accuracy of a millionth of an inch. With these instruments, current wire gauges like the Birmingham Wire Gauge could be measured and described in inches. This was done by Holzapffel together with Peter Stubs Jr, and their work was published in 1847 [11]. The results are listed in Table 1. They express the empirically derived Birmingham Wire Gauge in inches. Not surprisingly, Whitworth suggested a redefinition of the gauge as 1/1000 in. [12], as the French and Germans had done.

Increasing industrialisation and international trade forced the authorities to denominate a standard. Without a standard, it was impossible for an American firm to order wire in the UK without risking incorrect delivery. Without standards, the concept of interchangeable parts for machines was Utopian [13]. It was imperative to meet American demands because the USA had begun to lead the way in metal working in the 1870s [13].

Legal aspects

Is there one true gauge?

Most gauges lacked legal enforcement. In the USA, the Birmingham Wire Gauge, as described by Holzapffel and Stubs, was more or less recognised in acts of Congress and the US Steel Wire Gage was sanctioned by the National Bureau of Standards in Washington [14]. Because of close connections with the British industry during the early 19th century, British standards were tolerated.

A new Weights and Measures Act came into operation in the UK on 1 January 1879. It demanded that the same weights and measures should be used throughout the UK. The basis of measurement was the bronze Imperial Standard Yard. Some contemporary measures, derived from the Imperial Standard Yard, were included as secondary, so-called 'Board of Trade' standards. For example, this defined the inch as being 1/36 of the yard. Gauges were not mentioned in the act, but via an Order from Her Majesty in Council, such measures could be raised to Board of Trade standards, provided that they were equivalent to, or were multiples or aliquot parts of, the imperial measures. All trade contracts, sales and dealings should from then on be in imperial weights and measures. Deviating from this law incurred a penalty not exceeding 40 shillings for every sale.

In the 1880s in the UK, an effort was made to legalise and thereby save the gauge as an example of British quality. This process of legalising an historical and empirical measure illustrates the struggle between history, old habits, science and reality.

At that time there were four schools of opinion regarding the gauge:

1 Abandoning the gauge and adopting the French decimal metric system. This was the opinion of Holtzapffel in 1856 [4], Joseph Whitworth in 1857 [12] and J. Fernie in 1859 [15], the last two being chairmen of the Institute of Mechanical Engineers. They considered the gauge to be irregular and outdated because of the availability of micrometers. This idea was also adopted by a meeting of the Mechanics Section of the British Association. As a gesture, the gauge could be kept in use as 1/1000 in.

2 Maintaining the gauge, much like the Birmingham Wire Gauge, but with defined regular decrements. This option had already been suggested by the Liverpudlian James Cocker in 1858 [16]. The Wire Gauge Committee, which was instituted by the Associated Chambers of Commerce in 1879 after a suggestion made by Latimer Clark to the British Association [17], gave similar advice.

3 Maintaining the gauge, but in a real exponential decay scale with a base of 0.89, was advocated by Brown and Sharp in the USA in 1855, Clark in 1867 [8] and the Society of Telegraph Engineers in 1880 [18].

4 Maintaining the gauge with sizes that were the average of all known Birmingham Wire Gauges. This compromise was suggested by Thomas Hughes [7].

The above-mentioned Wire Gauge Committee considered all these propositions for a legalised standard wire gauge. Their considerations were published regularly in the *Ironmonger* [16], an established technical and commercial journal for the iron and metal trade.

Abandoning the gauge and adopting the micro-inch was rejected. The micrometer was considered too troublesome for general use because of the sensitive screwing mechanism and it would be too difficult for a craftsman or tradesman to think and speak of '164 thousands of an inch' rather than '8 gauge'. The use of a limited number of well-defined and well-known sizes was considered important. Because the Weights and Measures Act did not tolerate fractions of inches, a real exponential scale or an average of existing scales was not possible. The gauge was to be maintained but needed to be defined as part of a perfect compromise of all the proposals, laws and international developments. It should be closely related to the Birmingham Wire Gauge. The decrements should be in multiples of 4/1000 in., thus relating to the French metric system; 4/1000 in. being an acceptable approximation to a tenth of a millimetre (0.1016 mm).

In their first advice in February 1881, the Wire Gauge Committee obviously started from the Birmingham Wire Gauge (Table 1) but made the interval more regular. However, it was still not a strictly geometrical series.

This proposed standard wire gauge was discussed and amended several times. Local Chambers of Commerce feared that their own gauge would be abandoned and that Birmingham would play first fiddle. This period was described in the *Ironmonger* [16] as the 'battle of the gauges'. Individuals and institutions tried to promote their own gauge; some suggested that pending patents on names such as the Hughes Wire Gauge played a role. In an attempt to please everybody, the Board of Trade made changes to the proposal, violating the initial architecture. This watering down of the proposal is reflected in the copy of a working sheet of an officer of the Board of Trade (Fig. 3), containing several substitutions and ending in desperation with a question mark! Eventually, common sense prevailed and the definitive proposal repeated the initial logical progression. The only deviations from this progression relate to the thickest and thinnest sizes.

On 23 August 1883, Queen Victoria at court in Osborne House on the Isle of Wight signed an Order in Council in accordance with the Weights and Measures Act, 1878. In this document, the term gauge or wire gauge is not used; it is called a Denomination of Standard. This denomination thereafter became known as the British or Board of Trade Standard Wire Gauge [19].

During the 11th General Conference on Weights and Measures in Paris in October 1960, the International System of Units (SI) was formulated. All British weights and measures were redefined in terms of the metric system. All gauges formally lost their legal existence in 1963. The metre is now the legal unit of length and is defined as the distance travelled by light in a vacuum in 1/299 792 458 s.

Discussion

A gauge is not one defined size or thickness. It is not an unequivocal unit of length. In fact, it originated at a time when there was no universal unit of length at all. It was born experimentally in the practice of the wire-drawers many centuries ago. A gauge was a range of sizes specific to one manufacturer or branch of industry. It was only later, when engineers were able to measure the existing gauges, that they could be expressed in fractions of an inch. The gauge that is used on needle packages corresponds with the US Birmingham Wire Gage, imported from the UK, or the British Standard Wire Gauge, defined in 1883 by an Order in Council.

The wire-drawing process started with gauge number 1, a wire ≈ 0.300 in. thick. Starting with thicker wires would demand more force than was then available. After the first draw, and hence reduction, gauge number 2 resulted. After the second draw, gauge number 3, and so on. When the quality and consistency of the material increased, it became possible to draw thinner wire with still higher gauge numbers. This explains why most gauges have higher gauge numbers for smaller sizes. When steam and waterpower became available for drawing, it became possible to start with thicker wires. Because the gauge numbers 1, 2 and so on were already used for the first wires, gauge numbers 0, 2/0, 3/0, and so on, were devised and used for the thicker wires.

The sequence of the sizes of a gauge is not linear. The sizes of the Birmingham Wire Gauge, measured and published by Holtzapffel [4], are presented in Table 1 and can be approximately expressed by the formula: thickness in inches $= 0.300 \times 0.897^{(\text{gauge number}-1)}$. This is an exponential decay curve in accordance with the law of decrease by constant proportion. In this formula, 0.300 in. is gauge number 1 and for each successive gauge number the wire is reduced to 89.7% of the preceding gauge number. Why this decrease by constant proportion? The size of the step or reduction for each draw depends on the cohesive strength, or Van der Waal's forces, in the material, proportional to the cross-sectional area of the wire. The wire breaks when the cohesive strength of the resulting wire equals the cohesive strength that has to be overcome during the reduction. This is the case when the reduction is 30%; by then the cross-sectional area of the part by which it is reduced equals the cross-sectional area of the resulting wire. Breaking of a wire during its production had to be avoided at all costs, so a large safety margin was chosen. The reduction should also not be too small because an unmanageably large number of sizes would result, suggesting a nonexistent accuracy. Between these limitations, an approximate 10% reduction was the ideal. So the sizes of the wire gauges were dictated by the properties of iron and the ancient process of wire-drawing. During the process of legalisation that resulted in the Standard Wire Gauge, a three-ruled algorithm was used to stratify the decrements. This algorithm is best shown in the proposal of the Wire Gauge Committee (Table 1). A step is always a multiple of 4/1000 in., as close to the Birmingham Wire Gauge as possible, and the next step is the same or smaller. In this way, the still somewhat irregular steps of the Standard Wire Gauge can be explained.

Governments, boards of trade and standards offices have tried to abolish the gauge, considering it to be inaccurate and old-fashioned. Reality, however, deviates from the views of officials, as is demonstrated by the packaging and description of needles in use today. The gauge must possess particular advantages in order to explain its persistence in the face of so many attempts to outlaw it. With a gauge system, there is a limited and defined number of sizes in use. This enables intermanufacturer and interproduct exchange and efficient stock control. To draw a comparison with clothing, it would be unwise to abolish sizes in clothing and simply sell dresses by the inch. The typical exponential decay sequence of the gauges is realistic and practical because each interval is in proportion to the wire's size. The final advantage is the simplicity of saying: 'hand me a 29G needle' instead of 'hand me a 13.6 thousandths of an inch needle'.

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